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EXPERIMENTAL SHORT-PULSE X-RAY DETECTION SYSTEM

THE BENDIX CORPORATION
Aerospace Systems Division
3300 Plymouth Road
Ann Arbor, Michigan

AUGUST 1971
FINAL REPORT

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16. Abstract

~~This~~ The report covers the experimental study program to establish the design requirements of an operational system that can solve the problem of concealed weapon detection on personnel, using low level radiation X-rays.

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SECTION 1

INTRODUCTION

An experimental study program has been carried out to establish the design requirements of an operational system that can solve the problem of concealed weapon detection. The system consists of an early warning magnetic subsystem, a real-time radiographic subsystem breadboard, and subsystem interfaces including triggering and bypass electronics. Design recommendations are made for the user architecture, permitting the system to be used under different inspection conditions. The following efforts were performed:

1. The feasibility and compatibility of the radiographic inspection subsystem was established via an experimental parametric analysis with the experimental breadboard detector components. These components primarily consisted of a fluorescent screen, an objective lens, an image intensifier tube, transfer optics, a television (TV) camera, image storage and display media, a pulsed X-ray source, and associated hardware such as X-ray filters and electronics, and time delay and pulsing circuits. Parameters of individual components were examined to determine the optimum detection subsystem as far as sensitivity, contrast, and resolution were concerned.

2. A variety of X-ray sources and source energies were investigated with X-ray voltages ranging from 40 to 300 kVp and including both cold cathode (field emission) and hot cathode (thermionic emission) devices. These devices were evaluated against several whole-body phantom configurations to establish optimum X-ray source voltage, current, pulse duration, and X-ray filter requirements.

3. The optimum interface of the two detectors and the parameters of the associated display/control subsystems were determined, resulting in the definition of the most reliable and realistic detection system.

The manner in which these tests were conducted, results obtained, and conclusions reached are described in the body of this report. The final recommendations are given together with system specifications for recommended prototype configurations.

SECTION 2

RADIOGRAPHIC SUBSYSTEM OPTIMIZATION

The components of the breadboard short-pulse X-ray detection system which have been under evaluation consist of a pulsed X-ray source, a short-pulse X-ray detector, a single-pulse video tape storage unit, a video monitor, and a synchronizing control console. The system is shown in block diagram in Figure 2-1.

The principle of operation of the system is as follows:

1. A short pulse of X-radiation is emitted from the source. This beam casts an X-ray shadow of the suspect on the detector. The contrast of the shadow is dependent upon the absorption and scattering of the object and its background medium.

2. The detector converts this X-ray shadow to a visible image, amplifies the amount of light available, and converts the amplified visible image into a video signal.

3. The video signal is stored in a modified single-pulse tape recorder, or in a solid-state storage unit, and is immediately played back over the TV monitor for operator inspection.

The radiographic detector consists of a fluorescent screen, which converts the X-rays to light and thus produces the visual radiographic image; and objective lens, which images light from the fluorescent screen onto the photocathode of an image intensifier tube; a transfer lens or fiber optics, which images light from the output phosphor of the image intensifier tube into a TV camera; and the TV camera, which provides the electrical output signal to the recording or storage system. Several breadboard configurations of the radiographic detector were considered.

The various candidate components considered for use in the radiographic detector were evaluated experimentally at Bendix,in Ann Arbor, Michigan. Direct comparison of system performance as a function of component variation was the primary criterion in the evaluation. Secondary criteria included cost, size, and weight, and ease of assimilation into the remainder of the system. The various elements of the system are treated below.

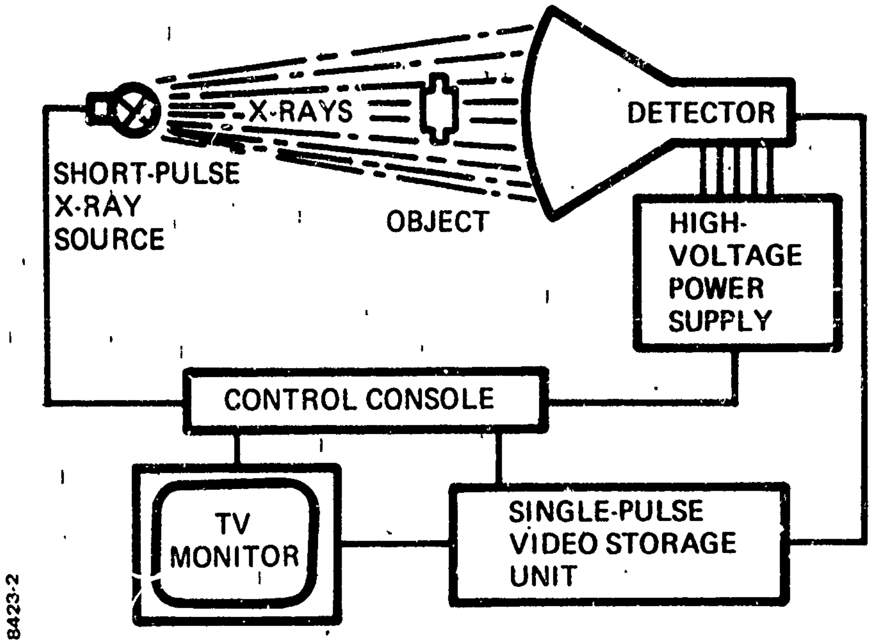

Figure 2-1 System Block Diagram

2.1 X-RAY MACHINE EVALUATION

The present program evaluated both thermionic and cold cathode X-ray sources. The specific equipment used included: an air-cooled Sperry machine with 160-kVp and 5-mA capability; a Balteau machine with 300-kVp and 5-mA capability; a Field Emission Corporation Fexitron cold cathode source operating at either 100 or 150 kVp; and a General Electric Maxitron with 1-MVp and 3-mA capability operating from 600 kVp to 1 MVp.

The primary parameters evaluated with these sources were penetration of human-equivalent targets (contrast) and over-all dose to the inspected subject (radiation safety). The technique employed in source evaluation was first to achieve the best penetration as indicated by the contrast of the final image and then to reduce the radiation dose by one of a variety of techniques.

2.1.1 Cold Cathode Source

It was found that the cold cathode source did not have sufficient penetration power. Although the rated output of the device was 150 kVp, the picture quality obtained corresponded more nearly to half that value. This determination was verified with the Sperry source. This effect is probably due to the physics of operation of the device, in that a triangular voltage pulse is used to produce the X-ray beam, rather than a pseudo-constant potential. The inherent advantage of the Fexitron is its compactness and very short pulse length (60 nsec). However, the absence of any useful penetration capability against a thick, scattering target makes the device totally unsuitable.

2.1.2 Hot Cathode Sources

The mode of operation of the thermionic devices is totally different. The X-ray beam is produced by continuously accelerating electrons toward a target, resulting in a typical bremsstrahlung X-ray output spectrum as the electrons give up their kinetic energy within the massive target block. Two methods were employed to pulse the output of such a device: mechanical shuttering and electronic pulsing.

The mechanical shutter investigated consisted of two overlapping lead sheets of sufficient thickness to almost completely eliminate a measurable output from the machine. For the 160-kVp source, 0.125-in. of lead was used, while for the 300-kVp source, 0.250-in. lead shutters were made. In operation, the two halves of the shutter are driven open by one or more solenoids, actuated momentarily. The shutter then closes automatically under the action of a strong spring. The exposure times achieved by this technique are on the order of 100 msec (0.1 sec), corresponding to about six fields of video data. The heavier mechanical shutter is shown in Figure 2-2.

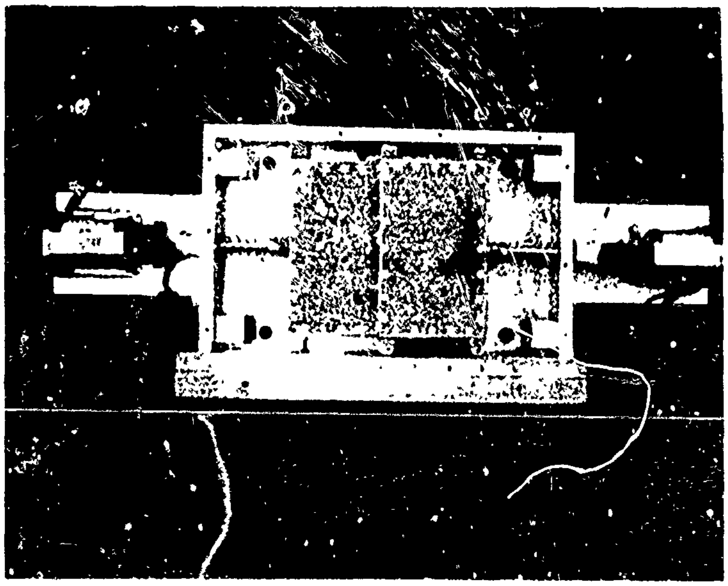

Figure 2-2 Mechanical Shutter

One of the effects of using the mechanical shutter which should be noted is that the radiation dose delivered to the object being radiographed varies spatially with the direction of shutter movement. The radiation dose is higher in the center strip of the beam and lower at the two extremities, since the shutter stays open longer in the center. If the suspect is centered, a mechanical shutter of this type is advantageous in that any individual is thickest at the center. In the case of an individual off-center, such a shutter could lead to loss of contrast.

The feasibility of electronically pulsing a thermionic emission X-ray tube was also investigated. The high-voltage supply to the X-ray diode was interrupted electronically to give pulses ranging from 1 msec (the frequency of the internal high-voltage supply) to 15 msec in length. The X-ray machine selected for modification was the Sperry 160-kVp, 5-mA unit. All the modifications were performed on the X-ray control circuits rather than on the X-ray tube head electronics.

The Sperry X-ray tube plate is driven by an ac voltage of approximately 1 kHz from the control unit. The filament voltage is taken from the plate supply voltage through a resonant circuit. Filament current is controlled by varying frequency as a function of plate current.

In normal operation, the control unit holds the voltage to the tube head at a low level during a warmup period after the X-ray button is pushed. This low voltage produces approximately 40-kVp X-rays during warmup. Also during the warmup time, the frequency is changed so that the filaments receive normal current even though the supply voltage is low.

Thus, due to the dependence of the filament supply on the plate supply, it is not possible to pulse from zero X-ray voltage to full output unless the tube head is also modified to permit a separate filament supply. However, the latter route was not attempted since the 40-kVp X-rays produced during warmup would not leave the tube head when a normal biological filter of 91 mils of aluminum is used for inspecting suspects.

The first attempts to pulse the thermionic machine were via the circuits in the control unit which reduce the voltage during warmup. It was found that the response of these circuits was too slow to produce the short pulses required.

The block and circuit diagrams of the electronics which were successfully used to produce X-ray pulses of a few milliseconds in length are shown in Figure 2-3. A 100-ohm and a 2-ohm resistor are in series with the tube head to reduce the voltage to the 40-kVp output level with the voltage knob on the control unit set to 160 kVp. When the button on the pulse circuit is pushed, the 100-ohm

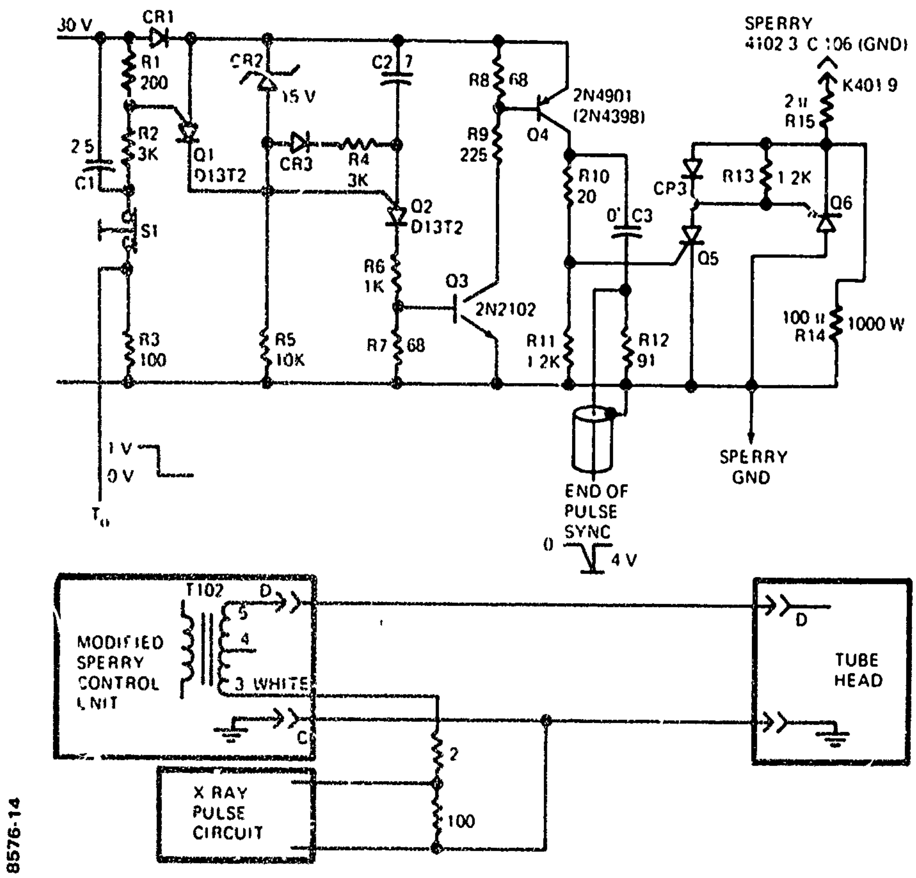

Figure 2-3 X-Ray Pulse System

resistor is shorted out for the duration of the pulse, which allows full voltage to be applied to the X-ray tube. The 2-ohm resistor remains in series with the tube head in order to minimize the effect of the tube head impedance on the series SCR inverter in the control unit when the sudden change in load is made.

As shown in the block labeled "Modified Sperry Control Unit" in Figure 2-3, a change was made in the control unit. Terminal 3 of T102 which normally is connected to ground was brought out to the series resistors in the pulse circuit. This allowed the resistors to be in series with the tube head, while synchronizing signals from the pulse circuit could be with respect to ground.

S1, a normally closed pushbutton switch, is the switch that initiates the pulse circuit. When S1 is actuated, a negative step voltage is available at R3 for synchronizing. Q1, C1, and R2 provide an initial delay before the pulse. Q2, C2, and R5 determine the length of a pulse which turns on Q3, Q4, Q5, and Q6. They in turn short out the resistance R14 in series with the tube head. A negative pulse signaling the end of the X-ray pulse is available at the top of R12.

Using this technique, X-ray pulses having the wave shapes shown in Figure 2-4 were obtained. Pulse durations up to 15 msec were possible. The dose at 7 ft from the machine for this pulse duration was approximately 0.1 mR. Attempts were made to extend this pulse duration, but stable, reliable operation was not achieved.

2.1.3 X-Ray Source Filtering

Significant parameters of any X-ray source from a radiographic point of view are: (1) peak kilovoltage and (2) filtration.

The theoretical output of a thermionic X-ray machine is as shown in Figure 2-5 for both the Sperry and the Balteau devices. What is important here is the relative amount of high-energy photons in the beam. The importance of this parameter arises from two effects. First, the high-energy quanta are less attenuated by the low-Z (atomic number) materials in the human body than are lower energy quanta. The same is true for the medium-Z materials of typical metallic objects, but because of the increased Z, to a lesser extent. This results in improved contrast in the radiographic image between the metallic object and the surrounding body tissue.

The second effect is due to scatter within the target itself. The primary attenuation mechanism in low-Z material (water has a Z of $\approx$ 8, steel (iron) of 26) is scattering at the energies of interest. Thus, the lower energy quanta do not penetrate as well, and when they do interact with the target complex, they produce scatter which further degrades the contrast of the radiographic image.

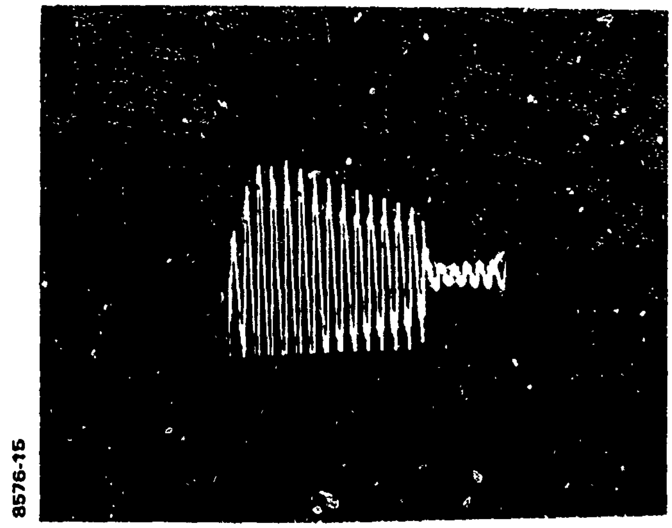

Figure 2-4 X-Ray Output Pulse
(15-msec Long)

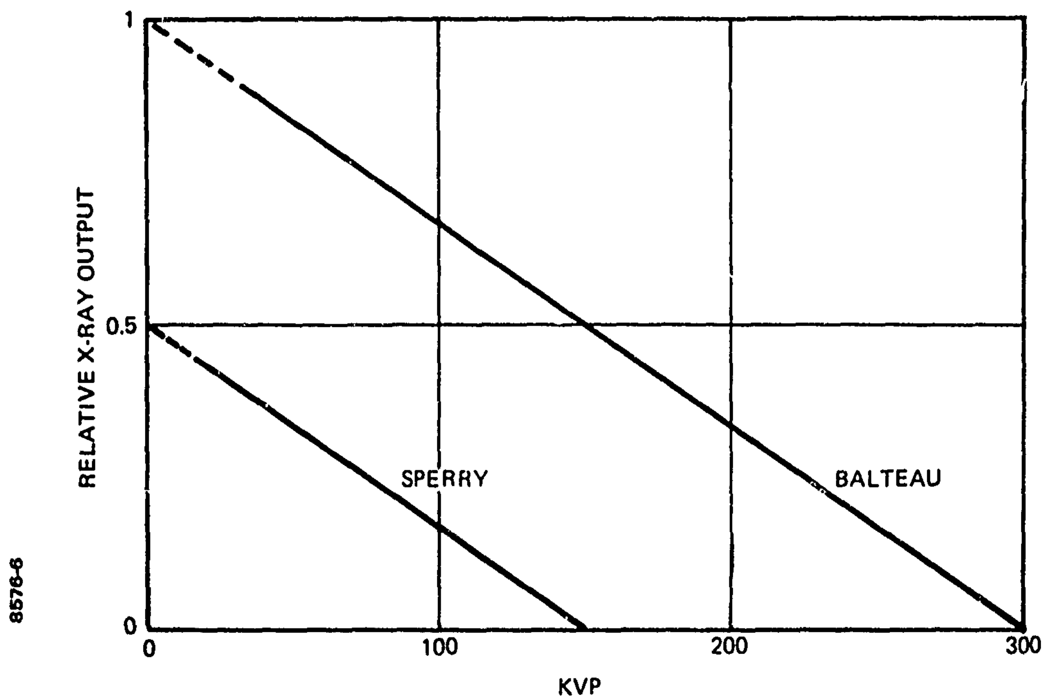

Figure 2-5 Theoretical Bremsstrahlung Output Spectrum (U)

The best imagery obtained with the Sperry machine was at its maximum kVp rating. When the Balteau became available, the best results were at its maximum of 300 kVp. Tests were thus performed at higher voltages.

Consideration of Figure 2-5 shows that, for any given value of kVp, most of the output spectrum is contained in lower energy quanta. These photons contribute to the measured X-ray dose but serve primarily to degrade the contrast of the radiographic image. This effect is offset by the use of filter materials at the output of the X-ray source. These materials preferentially reduce the fraction of low-energy photons in the beam as shown in Figure 2-6. Again, the primary attenuation mechanism is scattering, but the relatively large separation between the source and the screen prevents the scattered radiation from reaching the screen and degrading the image.

In the work done with the 300-kVp machine, a filter of 0.182-in. aluminum (Z-13) was found to be optimum. This is in addition to the inherent filtration built into the Balteau machine of 5.5-mm (0.217-in.) aluminum. Thus, a total of 0.4-in. aluminum is obtained. The corresponding best value for the 160-kVp machine was found to be 0.091 in. of aluminum. Other materials evaluated were iron (Z=26), copper (Z=29), molybdenum (Z=42), tin (Z=50), lead (Z=82), and uranium (Z=92). For equivalent output doses, very little difference was noted between iron, copper, and aluminum. The heavier metals did not give as good a picture, but there was not sufficient variation in material thickness and X-ray output to ensure a conclusive result.

In the case of the 1-MVp machine, in the Army effort, steel and lead filters were used to good effect. The optimum filter was found to be 1/8- to 1/4-in. lead at the 1-MVp rating.

2.1.4 X-Ray Source Dose Variation

In the X-ray energy regions of interest, all the usual units of radiation dosimetry are equivalent. Thus, the roentgen and its subdivisions were used throughout the program. The outputs of the 160- and 300-kVp hot cathode machines used are shown in Figure 2-7. The data are given as dose rates, assuming no pulse capability.

Once a satisfactory value of filtration is established, there are three ways the X-ray dose may be reduced for a given hot cathode machine operated at a given X-ray kilovoltage (1) the tube current may be lowered; (2) the pulse duration may be shortened; and (3) the source-to-target distance may be increased. (In the case of commercial cold cathode devices, the pulsewidth and the current are, of course,

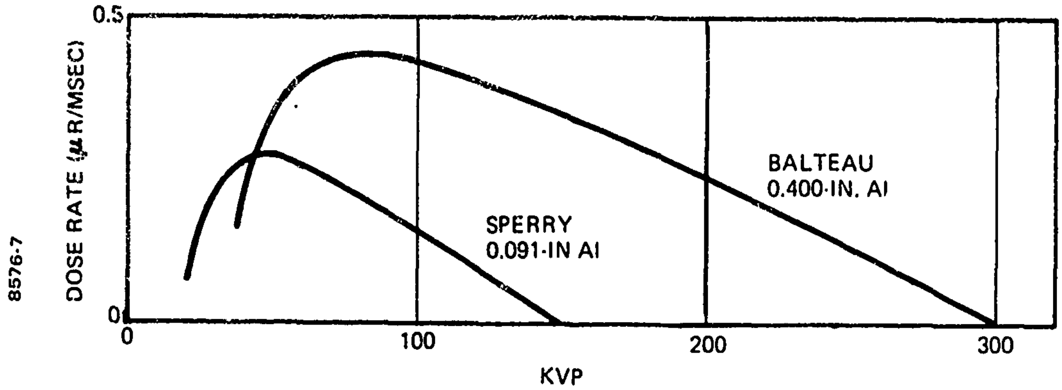

Figure 2-6 Filtered Bremsstrahlung Spectrum

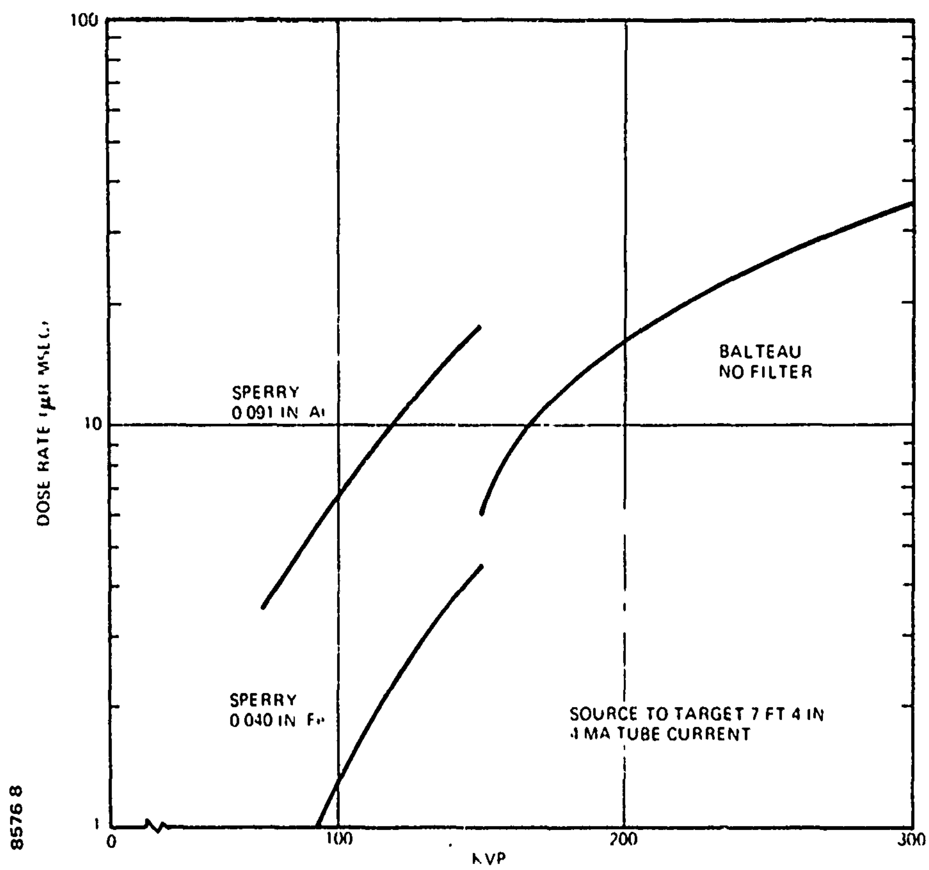

Figure 2-7 X-Ray Dose of 150- and 300-kvp Machines

fixed, the pulse duration is between 20 and 60 nsec, and the current is in the kiloampere range. Dose can only be varied by distance changes, filtering, and by gross kilovoltage variation).

Varying the tube current was the only one of the three methods which was routinely employed. Figure 2-8 shows the dose variation with current of the Balteau machine for a given peak kilovoltage. It is seen that the variation is not linear over a significant range; thus, current variations should only be made with the aid of such curves.

The variation of the mechanical shutter open time toward shorter values can be accomplished to pulse lengths as short as one video frame (≈ 30 msec). Thus, a dose reduction factor of three may be anticipated with a more rapid mechanical device than the present 0.1-sec shutter.

The variation of source-to-target distances was limited somewhat by the physical space limitations in the laboratory area. However, since an inverse square law applies, the distances involved grow quite rapidly. The baseline geometry employed a maximum source-target separation of 8 ft. Thus, a factor-of-four dose reduction would have increased this to 16 ft, resulting in an over-all length of about 25 to 30 ft. This latter value could not lend itself to ease of installation and/or camouflage.

In the final analysis, an optimum combination of the three parameters (current, pulse duration, and geometry) is required to achieve the minimum possible dose, as far as the hot cathode X-ray source is concerned.

2.2 RADIOGRAPHIC SCREEN MATERIAL

Various materials are normally employed to convert X-ray quanta into visible light. The two major groups are crystals (NaI, CsI) and powders (ZnS, ZnCdS, $CaWO_4$). One crystal sample (CsI) and two commercially prepared powder screens (ZnCdS and $CaWO_4$) were tested to determine their relative light output as a function of input X-ray dose.

The technique employed an RCA 4463 photomultiplier tube having the same spectral response characteristic as the image intensifier to be used in the detector. The output of the 4463 was read with a Hewlett-Packard 425A voltmeter. The resulting data, in the form of millivolts output vs. milliroentgens X-ray dose input, are given in Figure 2-9. These data were taken at 100 and 150 kVp, with dose variations at each energy achieved by filtration and/or separation changes, so that the data are not specified to output spectrum of the source.

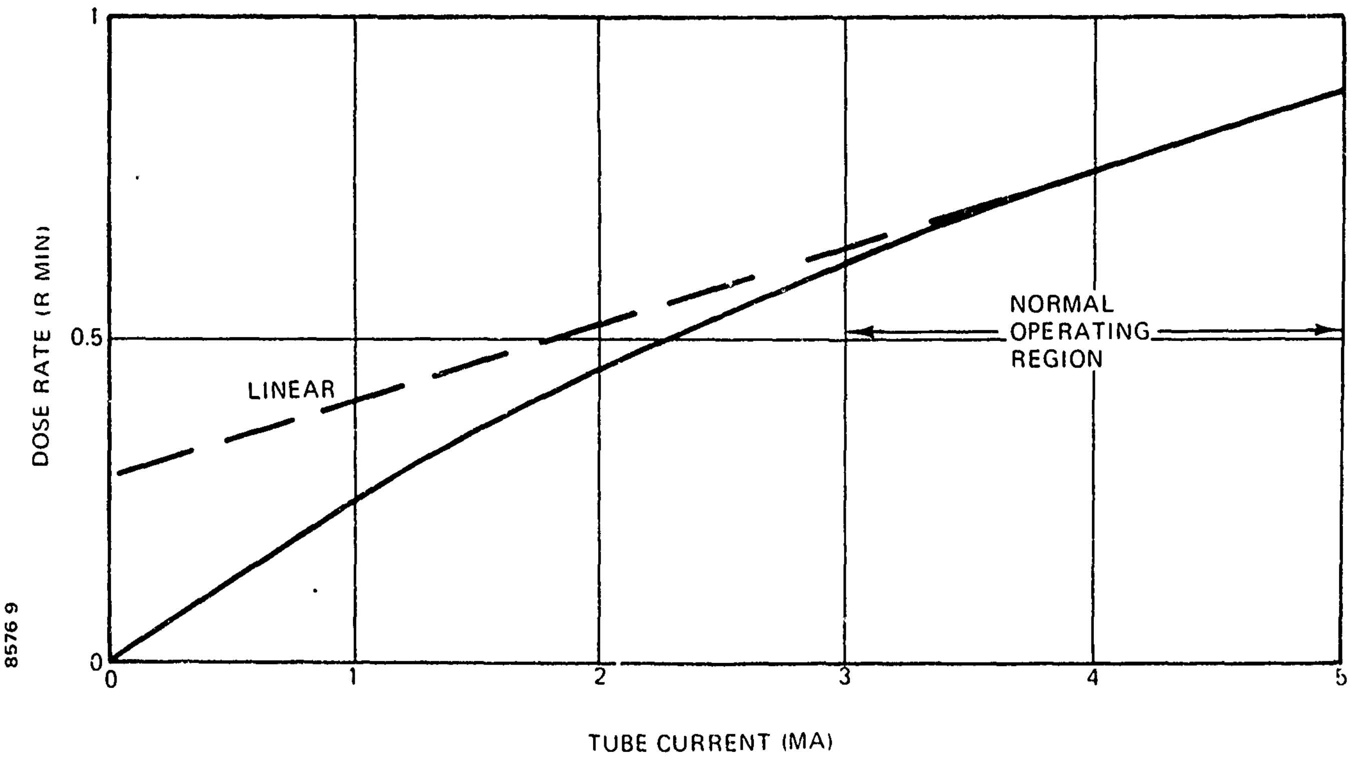

Figure 2-8 X-Ray Dose vs. Current for Balteau Machine at 200 kvp

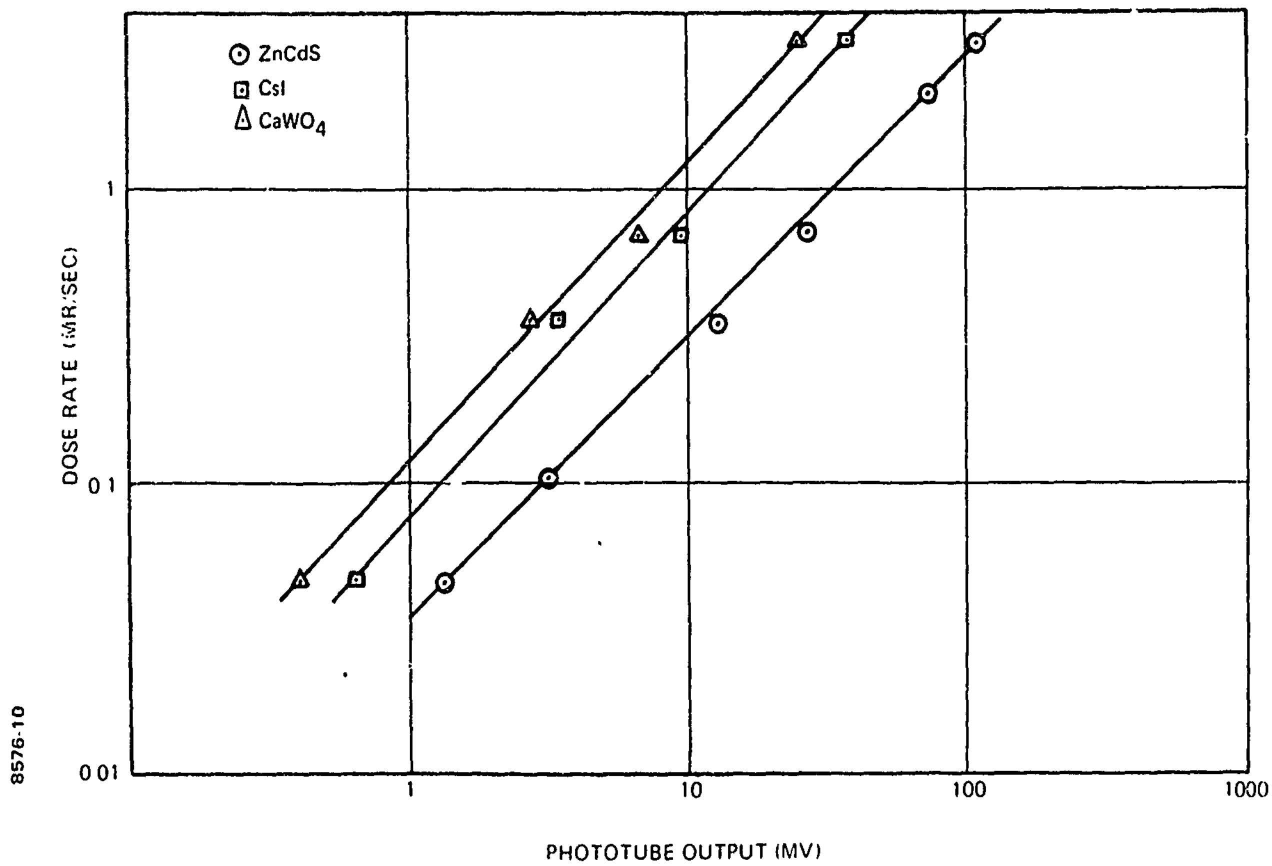

Figure 2-9 Comparison of Various Screen Material Outputs

The above results were subsequently checked with the 300-kVp machine. The crystal material (CsI) surpassed the ZnCdS efficiency at the higher kVp range. However, since the material is not practical for this application, no revision of the result is obtained.

No serious consideration was given to the relative resolution capabilities of the various materials, as the minimum value exceeds any reasonable system requirement. This value is quoted as 3 ℓ p/mm which, over 8 ft of screen, results in an image containing in excess of 2400 ℓ p. The nominal capability of the image intensifier is 25 ℓ p/mm over 38 mm of image format, i.e., 1140 ℓ p. Thus, even the minimum available screen resolution is a factor-of-two greater than the detector system can accept and presents no problem.

2.3 OBJECTIVE LENS

The requirements on the objective lens are to image a dim, yellow-green 8- by 3-ft shadowgraph formed on the ZnCdS screen onto the 38-mm-diameter photosensitive surface of the image intensifier. The selected lens must accomplish this 64:1 minification of the X-ray image with a minimum of distortion and contrast reduction, and a maximum image uniformity, while providing the maximum possible light collection efficiency.

Two candidate lenses were evaluated in the radiographic system. The first was a Canon F/0.95, 50-mm focal length lens specially modified to provide a 38-mm output format. The second lens procured for the FAA Program was an f/1.5, 18-mm focal length lens custom made by Angenieux Corporation of France. Both lenses are distortion-free over their image format and have excellent contrast transfer characteristics as estimated by relatively unsophisticated techniques. The Canon lens exceeds the Angenieux in collection efficiency by at least a factor of 2.5. Since the relative lens transmission values were not measured, this represents the square of the ratio of their f/numbers. However, the Angenieux can be fabricated with a speed of f/1.0, if some mechanical modifications to the input end of the image intensifier are permitted.

The primary reason for eventual selection of the Angenieux over the Canon is its short focal length. For an image format of 38 mm, a 50-mm focal length gives a field-of-view (FOV) of 41.6°, while an 18-mm lens gives an FOV of 92.8°. To cover an 8-ft format, the long lens (Canon) requires a spacing of 10.5 ft, while the Angenieux needs only 3.8 ft. Thus, the purely mechanical constraint of efficient use of space leads to the selection of the shortest focal length possible.

2.4 IMAGE INTENSIFIER

The image intensifier is the heart of the radiographic detector subsystem, amplifying the very dim image provided by the fluorescent screen-objective lens combination to levels suitable for human observation. Two different classes of intensifier were evaluated, differing in internal focusing mechanism.

Magnetically focused intensifiers are very high gain devices (up to 6×10^5 in a three-stage and 2×10^6 in a four-stage configuration), which exhibit very little distortion and have relatively good contrast transfer characteristics. The only disadvantages are the large permanent magnet around the tube (or a solenoid, which is an available alternative), which causes interface problems with the TV camera, and the fact that fiber-optic output surfaces result in a gain loss of 2 from the above figures. A power supply and voltage divider network is finally required for operation of these tubes. The size of these is not a problem for the FAA application.

Electrostatically focused intensifiers on the other hand have lower gains (typically 35,000, but 100,000 in three stages can be attained) and exhibit serious pin-cushion distortion. Electrostatic tube contrast transfer is usually better than the other type, but the difference between individual tubes within a class is sometimes larger than the difference between the two classes. Electrostatic tubes have the advantage of fiber-optic input and output interfaces. The power supply is tiny and consists of a 1-cu in. inverter and a 6-Vdc battery.

During the program, an RCA 8606 and a special Varo 8606 three-stage electrostatic tube were used to evaluate this type of tube and the feasibility of fiber-optic output coupling. The gain and distortion drawbacks were found to preclude use of this type of tube in the FAA application. Attempts by Varo to produce a distortion-free image resulted in severe reduction of image size from 38 to 25 mm.

The magnetic tube used was an RCA C70021 ZP1. Two tubes were evaluated, having nominal luminous gains of 260,000 and 590,000, respectively. The resolutions available when viewing a high contrast image—black and white bars ($\approx 90\%$ visual contrast)—were 25 and 23 ℓ p/mm, respectively, for the low- and high-gain items. This is an insignificant difference.

2.5 TRANSFER OPTICS

The function of the transfer optics is to image the output of the intensifier on the photosensitive surface of the TV pickup tube. This can be done by using either lenses or fiber-optic elements. Again, as with the objective lens, minimum

distortion and contrast degradation, coupled with maximum light collection efficiency, are desired. Here, however, the minification is only 4:1. There are also other considerations arising from the presence of high-dc voltages at the output of the intensifier and, in the magnetic tube case, the effects of the field of the permanent magnet on the alignment coils of the vidicon.

2.5.1 Lenses

Several lenses were evaluated for the image transfer function, including a Canon f/0.78, 25 mm; a Carl Meyer f/1.1, 36 mm; and a Canon f/0.95, 50 mm. The f/0.78 lens has the best collection efficiency; however, the short focal length of this lens brings the vidicon into very close proximity to the intensifier magnet. The solenoidal field of the magnet is about 150 gauss in this region and causes an extreme compression of the vidicon scanning field. The beam deflection and focus coils cannot overcome this static field to provide normal operation. This focal length lens is therefore unusable with a magnetic tube.

The 36-mm lens is the shortest focal length which will allow operation of the vidicon, and even with this lens, realignment adjustments are necessary. Some shading of the video output toward the bottom of the scan is present, which is attributed to the remaining effect of the magnetic interference. The light collection efficiency of this lens is the lowest of the three lenses evaluated.

The lens finally selected was the 50-mm, f/0.95 Canon. This is the same basic lens evaluated as an objective, except that since the normal 16-mm format is used, it required no modification. This lens presents the optimum available combination of speed and separation for use with a magnetic tube and a vidicon, determined in the program.

2.5.2 Fiber Optics

As mentioned previously, tests were performed with an RCA 8606 intensifier having a fiber-optic output interface. An 8507A fiber-optic faceplate vidicon was obtained which differs only from the normally used vidicon in having a fiber-optic faceplate. A 3-in.-long bundle of 10-μ fibers was produced having a 35-mm format at one end and a 16-mm format at the other.

The resulting image transfer system was assembled without employing the usual interface bonding techniques. The fiber-optic breadboard showed an apparent improvement of 6 to 8 in system gain over the Carl Meyer 36-mm f/1.1 lens. The 3-in. bundle length was required to stand off the 45 kVdc present at the output end of the electronic tube. In addition, a slight noise problem was encountered due to the fact that the vidicon face (0-V potential) was in close contact with the tube.

The power supply is a 2800-V, 1500-Hz inverter and some of this signal "leaked" through to the face of the vidicon where it was amplified and presented as an unwanted part of the video output. Grounding of the bundle via an aluminum foil cover was employed for a successful reduction of this noise to an acceptable level.

2.6 TELEVISION CAMERA

2.6.1 525-Line Camera

One of the TV cameras evaluated in the radiographic detector was a Sylvania 800 using a GE 8507 separate mesh vidicon. The camera was modified to allow remote operation of the vidicon level and beam focus controls, as well as mechanical focusing of the vidicon yoke assembly within the camera housing. Further electronic modifications were incorporated to allow both horizontal and vertical image inversion, since the output of the intensifier is normally inverted, and to allow image integration on the surface of the vidicon.

Other camera tubes were also evaluated in the Sylvania camera. These included an orthicon, a vidicon without the separate mesh feature, and an image storage tube, the Permachon. None of these tubes showed the uniformity of performance that the 8507 vidicon displayed.

Low-light-level TV cameras, including the isocon and an intensified vidicon, were evaluated on a loan basis. Both items showed an increase in sensitivity over the baseline system. The isocon had a significant blooming problem and did not present an improvement sufficient over-all to warrant further consideration. The intensified vidicon was a straightforward system improvement requiring only the payment of a cost penalty. Due to the loan nature of the evaluation, only video tape comparisons were made of system performance.

2.6.2 1029-Line Camera

The final TV camera evaluation was performed on a 1029-line system procured for the FAA Program. The system procured, the GEC/ED6073 high-resolution camera, did not exhibit the same sensitivity as the 525-line system. Higher resolution imagery was obtained under normal room lighting conditions, with the most striking aspect of the performance being the inability of the observer to perceive the scan lines in the display, giving an apparently uniform image.

However, when the system was adapted to the radiographic detector, no such performance was apparent. Video sensitivity was decreased by as much as an order of magnitude. Three hypotheses were made, only one of which was

disproved due to time pressure and the fact that the 1029-line capability was not directly required. This involved the possibility of a spectral mismatch between the P-20 output of the intensifier and the photosensitive surface high-resolution vidicon. A careful check of the manufacturer's specification was made, and a tube replacement was obtained to no effect. It can thus be stated that the problem of lack of sensitivity was not due to spectral mismatch.

The other two hypotheses were: (1) the increased video bandwidth of the 1029-line system over a 525-line system, in the presence of a given signal level, would result in a decreased signal-to-noise (S/N) ratio; and (2) the specific electronic hardware delivered is substandard.

In a final effort to reclaim the high-resolution camera system, a single-stage, proximity focused Bendix 749 diode amplifier was obtained on loan and was fiber-optically coupled to the camera. This diode provides a nominal luminous gain of 30 and could have allowed normal camera operation. The results, however, were negative, indicating either insufficient gain or malfunction of the diode or its power supply.

This technique, when properly implemented, could enhance the system gain regardless of the TV pickup tube employed. However, this approach is identical to the use of an intensified vidicon. The economics of using a diode vs. an intensified vidicon remain to be investigated.

2.7 VIDEO STORAGE UNIT

Two primary techniques were employed for recording and storing the short-pulse imagery obtained by the radiographic detector: a single-pulse video tape recorder (SPVTR) and a solid-state device, the lithocon. The former is only applicable to 525-line operation, while the lithocon is convertible between the 525-line and the 1029-line scan rate. With both storage devices, a continuous 1-in tape recorder was employed to record the 525-line test data in a permanent form.

A third recording technique, the video disc, is also possible. The technique was evaluated prior to the start of the program. It was determined that the performance of the disc at 525 lines was comparable to that of the tape. However, the disc was found to be an extremely fragile device which developed magnetic head and disc breakdown problems, especially if the equipment were moved from location to location. The basic unreliability of the device was inherent in its basic premise - a metal disc revolving at high velocities a few mils away from a small head. This made alignment highly critical and particles of dirt disastrous. These considerations, added to the fact that the cost of the device is significantly higher than either the tape or solid-state recording devices, resulted in the elimination of the video disc from consideration.

2.7.1 Single-Pulse Video Tape Recorder

The SPVTR is a Sony 310, 1-in. tape recorder extensively modified to perform the single-pulse storage function. Its operation is as follows. The signal which activates the X-ray pulse is used, after suitable delay, to activate the record function in the SPVTR. The next field (one-half of a video frame) is recorded on the stationary video tape and the SPVTR refuses all subsequent incoming signals from the camera. The recorded image is then "read" to a modified TV monitor and/or recorded on continuously moving video tape in the usual manner. A reset function advances the stationary tape and prepares the system logic to begin the cycle anew. The circuit changes performed and the control circuit for the recorder are shown in Figures 2-10 through 2-12.

The image thus obtained contains only one-half the scan lines of a normal TV picture, since such presentations are made on a 2:1 interlace basis. Thus, final system output resolution is degraded by a factor of two. Depending on the position of the observer with respect to the display, this can be, at worst, noticeable in the small metallic object detection role. The SPVTR has operational flexibility and extremely good reliability to recommend it.

2.7.2 Solid-State Storage Device (Lithocon)

The lithocon "writes" the incoming field of video data on the silicon matrix instead of video tape, and then reads from this matrix to provide an output. The device is considerably more complex, providing level and focus controls for both the input and output functions, but does incorporate an automatic zoom function to enlarge a selected portion of the output image.

The primary reasons for evaluating the lithocon were that it provided a full 525-line picture - albeit of one field of data - and that it was the only available high-resolution recording device (up to 1200 lines). The control function prior to the device itself (i.e., timing, synchronization, field selection, etc.) is the same for both devices.

Two operational problems existed which made the lithocon the second choice as a component of the radiographic detector. The most serious was the very limited dynamic range of the device. Personnel inspection radiographs contain variations in brightness of approximately three orders of magnitude. The lithocon smeared the bright areas and/or erased all detail in the relatively darker areas of the image, making detection in the resulting image very difficult. The SPVTR has a much greater range of accommodation in this respect

The second problem had to do with the complexity of the device itself Very critical adjustment of focus and read controls were required to achieve the best

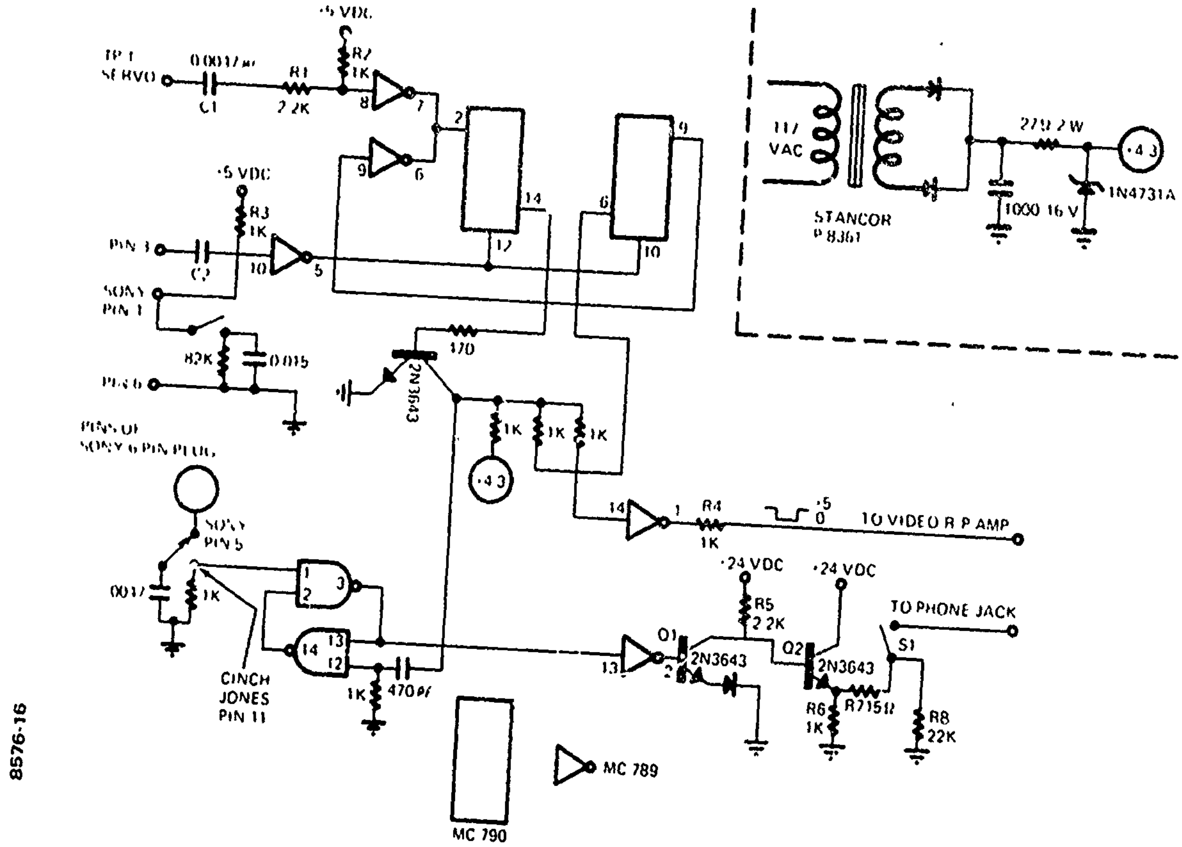

Figure 2-10 Sony EV-310 Timing Board Stop Action Modification Circuit Diagram

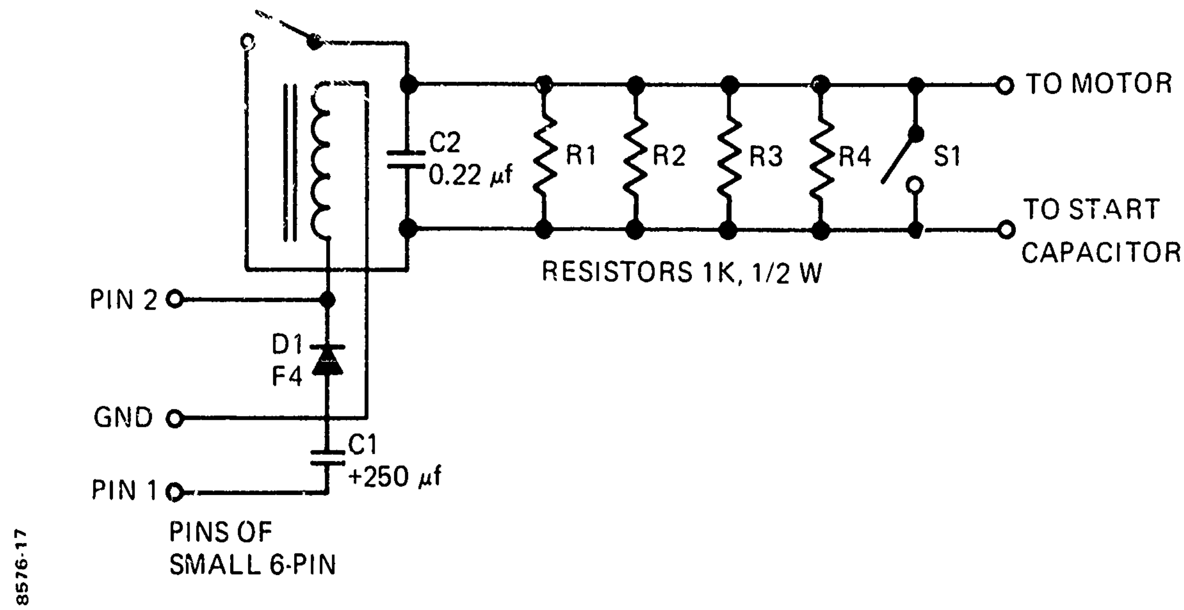

Figure 2-11 Sony EV-31C Relay Board Modification Circuit Diagram

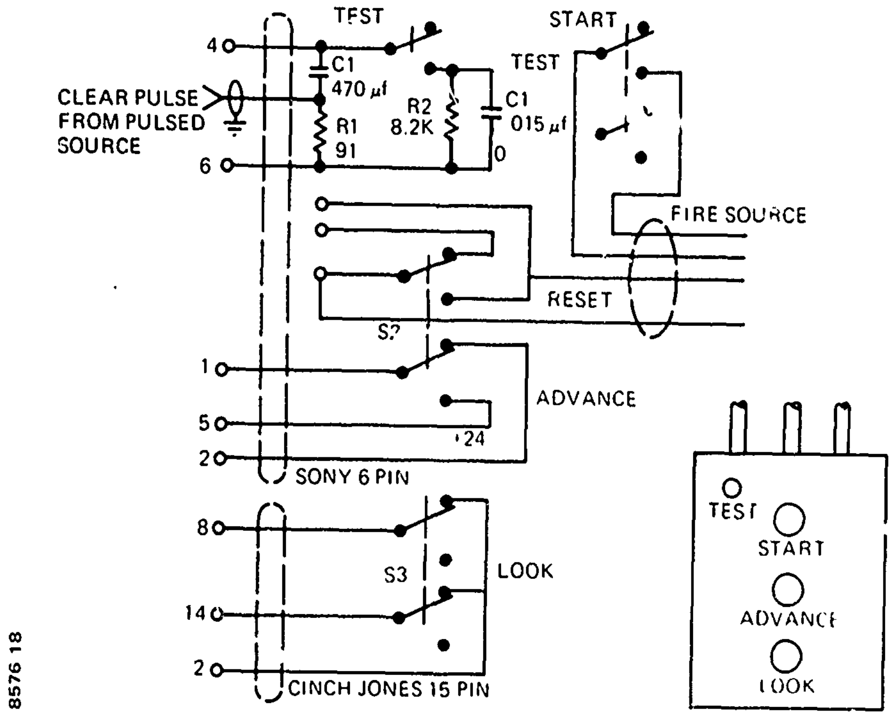

Figure 2-12 Sony EV-310 Special Remote Control Box
Circuit Diagram

output and care was required to prevent the read function from erasing the stored image too quickly. All in all, the lithocon could require a level of electronic sophistication not normally present in anticipated operational personnel.

Finally, the fact that a satisfactory high resolution television camera was not found tended to make the high resolution capability of the lithocon superfluous.

2.8 VIDEO DATA PROCESSING AND CONTROL ELECTRONICS

Three techniques for obtaining data were used. The first, which gave the highest quality output imagery, allowed the X-ray machine to operate continuously and actuated the recording mechanism to obtain one fixed field of data. This technique of recording one video field out of a continuous stream of such fields was called "pulse snatching." The technique is obviously not operationally meaningful and was used simply as the basis for all subsequent comparisons. The second technique employed was the truly operational one of pulsing the X-ray source and recording the best field of whatever video signal output occurred. The third technique involved the integration of as many as five fields of information created as a result of one pulse of X-radiation.

Initially, a large degradation in image quality resulted in going from the first to the second technique. Inasmuch as the operational technique is the only valid one, an immediate investigation into the loss of signal was performed. This was done by recording the pulsed X-ray output on a continuously running video tape recorder (CWVTR). The recorded data were then reviewed on a field-by-field basis It was found that the video output of the TV camera exhibited a well defined time lag in reaching full signal strength The X-ray pulse (0.1 sec) was known to encompass six to seven scan fields (1/60 sec each) and, of these, the third, fourth, and fifth usually provided the best imagery. This effect is due to the combination of the mechanical response time of the shutter - it could be seen opening and closing - and the time required for the vidicon to come to full output, as shown in Figures 2-13 and 2-14.

Thus, it was necessary to provide a time delay between actuation of the X-ray shutter and the initiation of the recording function in the SPVTR. The circuitry required to accomplish this is shown in Figure 2-15, along with that needed to pulse the mechanical shutter. Also shown in the figure are the details of the electrical interface between the electromagnetic and radiographic subsystems.

The resulting operational technique gave acceptable output imagery using both the SPVTR and the lithocon and became the technique finally employed in the breadboard detector. Good documentary data have been obtained by re-recording the single field image from the stationary tape onto the CWVTR. As is evident from

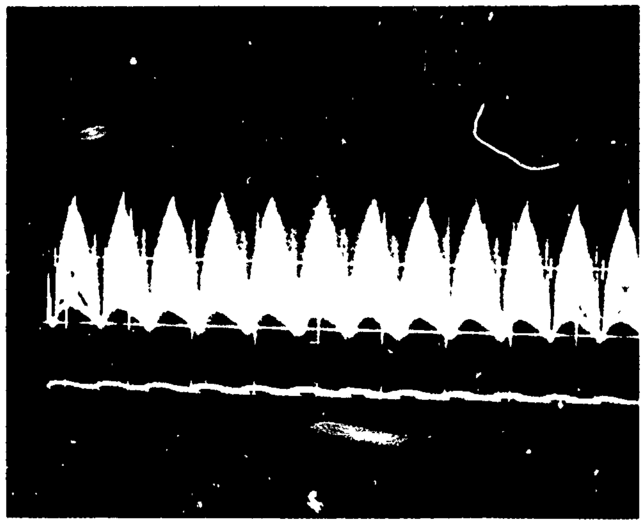

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Figure 2-13 Continuous Video Output Level (0. 2 V/Div, 20 msec/Div)

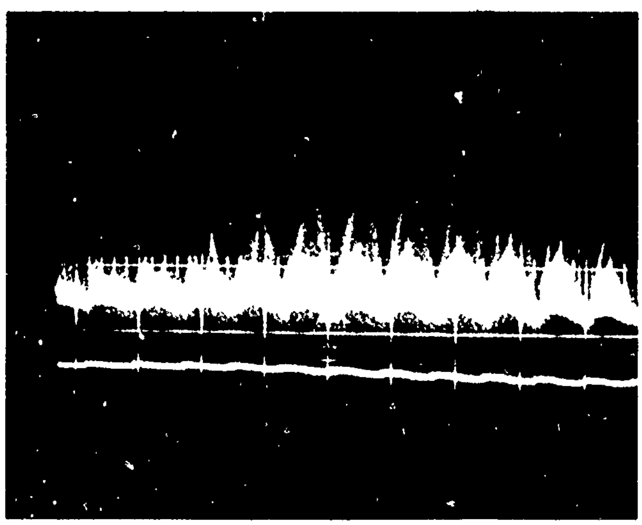

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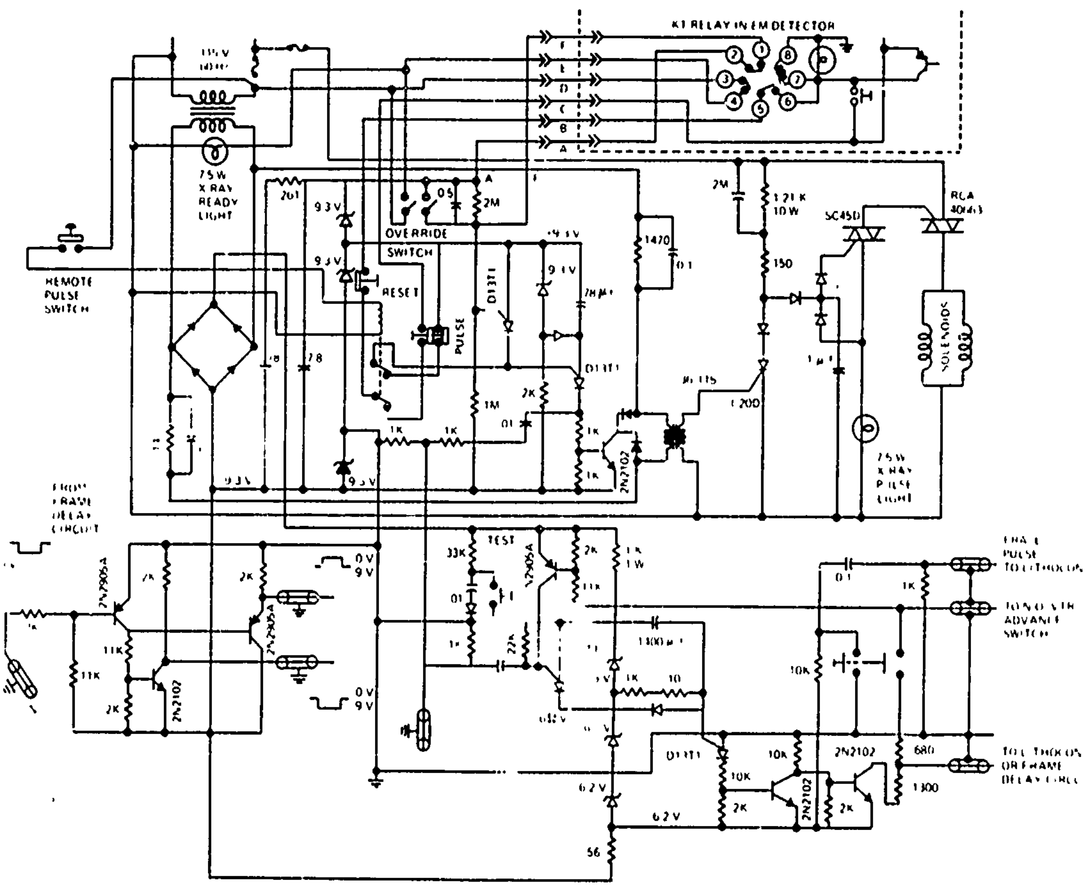
Figure 2-14 Pulsed Image Video Output Level (0. 2 V/Div, 20 msec/Div)



8576-5

Figure 2-15 Synchronizer (Shutter Control, Timing, and Pulse) Circuit Diagram

Figure 2-15, several additional electronic functions were required for interfacing with the lithocon. This was due to the nature of the new recording device and the fact that the original shutter drive circuit was designed specifically for use with the SPVTR, and vice versa. The circuits merely amplify and/or provide different DC timing pulses.

During the above investigation, it became obvious that no single video output field resulting from an X-ray pulse contained as much information as a comparable pulse "snatched" from a continuous series of pulses. In an attempt to compensate for this loss, since more information was generated by the system than was finally used, techniques for integrating the video output from successive fields during a pulse were investigated.

The integration technique was implemented with the frame delay circuit shown in Figure 2-16. This device was used in conjunction with both the SPVTR and the lithocon. When used with the SPVTR, in addition to the variable time delay circuitry discussed above, it allowed integration of up to five fields of input signal on the photosensitive surface of the vidicon. Essentially, the electron beam of the vidicon was turned off for a time period equivalent to from one to five fields and then turned back on to "read" the total charge built up on the sensitive surface during that period. In operation, it was found that from two to four fields of such integration gave the optimum image improvement, depending on original signal strength. Too little integration obviously gave no change in the result and too much caused an effect equivalent to "blooming" of the bright areas of the image.

The same circuitry was employed with the lithocon to enable the recording of up to five successive video fields on the silicon target of the lithocon without erasing in between. In this case, the frame delay was used simply to delay initiation of the lithocon "read" cycle. Essentially, the same result was obtained, except that the dynamic range limitation of the solid-state recording device reduced the number of fields which could be recorded together to two or three.

2.9 DOSE VARIATION WITH DETECTOR SENSITIVITY

The minimum dose applied to a suspect depends ultimately on the maximum sensitivity of the radiographic subsystem detector. The breadboard system that was used permitted some analysis of means of improving detector collection efficiency and thus reducing the radiation dose to suspect.

The most immediate means of improving system performance involves increasing the aperture of the objective lens to collect more light photons from the fluorescent screen. Tests performed with the 18-mm f/1.5 lens and the 50-mm f/1.0 lens indicated that an f/1.0 18-mm lens could be used to advantage, giving

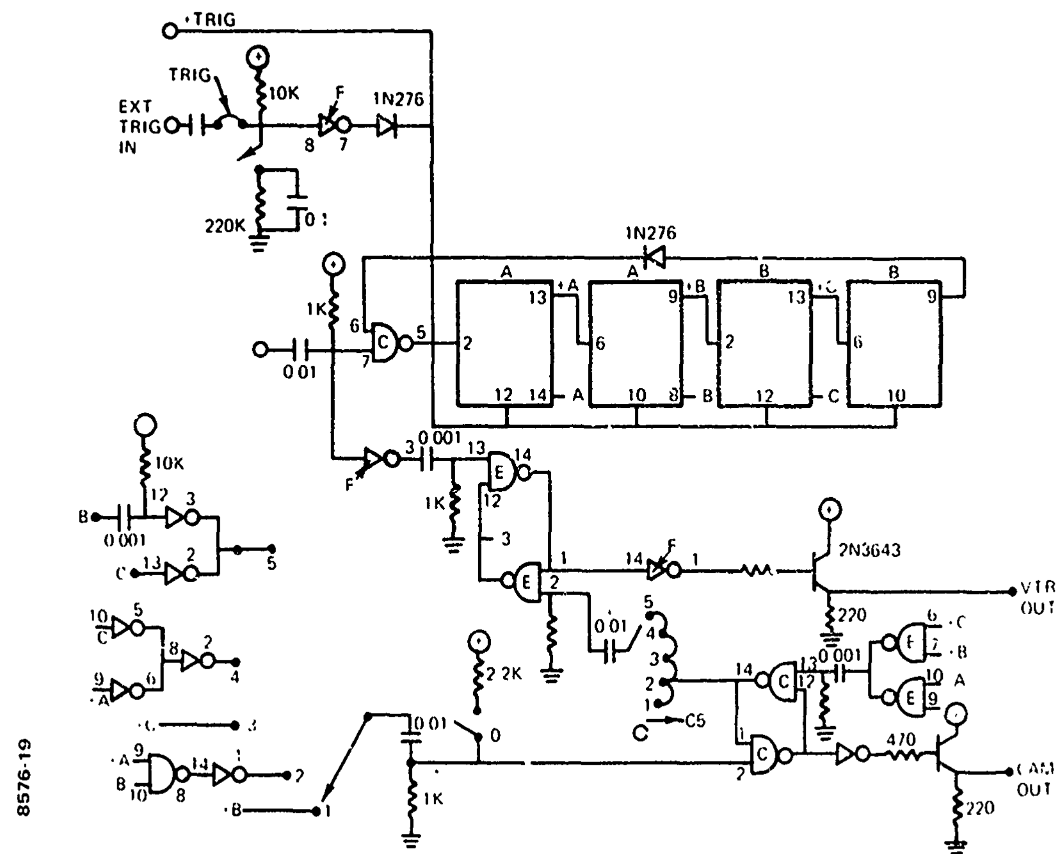


Figure 2-16 Integration Technique Circuit Diagram

a factor of 2.25 in theoretical light collection efficiency, and based on the experimental results, probably over a factor of 3 degrees in dose when the true relative apertures of these lenses are considered.

Improvements can also be made in the gain of the image intensifier tube. The laboratory experiments with the radiographic subsystem were conducted with intensifier tubes with nominal luminous gains of 260,000 and 590,000. It was determined that for a given objective lens aperture the latter resulted in a dose reduction factor of approximately two. From previous experience, it is known that image intensifier gains could be increased to a value between 1×10^6 and 2×10^6 before photon statistical limits and image degradation due to photon noise are reached. Higher gain tubes in this region should therefore result in dose reduction.

The third possible means of reducing dose would be to provide more light to the camera tube. This, as has been shown, can be effected by higher aperture transfer optics (including fiber optics) or by intensifying the light output of the image intensifier.

The term "gain" in connection with the transfer optics actually refers to a reduction of loss of available light in the system. Thus, in a sense, dose reduction is possible by a factor corresponding to the reduction of system light loss compared to a system which does not make use of a more efficient light collection and transfer.

The technique of image integration permits more efficient light collection in this sense and should therefore be preserved in a detector system, since it offers an easy means of maintaining minimum dose requirements. Integration allows full collection of the energy from a single pulse of radiation by the surface of the vidicon for later transfer on the storage device. Images are integrated over the time that the X-ray pulse exists on the output of the intensifier phosphor and then displayed with the accumulated signal energy in the image. It was determined that a much brighter image resulted when this technique was used. Hence, dose reduction is possible this way or the improvement in signal strength can be traded-off for an increase in detection camera resolution/contrast.

SECTION 3

SYSTEM EXPERIMENTAL DATA AND DISCUSSION

3.1 TARGET CHARACTERISTICS

Two types of targets were used to evaluate system performance: (1) plastic water containers in thicknesses up to 14 in. and (2) radiological phantoms containing human skeletons. Much of the early work was done with a water-filled plastic phantom on loan from The University of Michigan School of Public Health. Subsequent work with this target revealed that a thickness greater than 3 in. was required to simulate a human adult. Use of human test targets was not possible in this program because of legal restrictions; hence, simulation methods were used. The phantom used in early work is shown in Figure 3-1.

A second, thicker phantom was subsequently obtained on loan from the Washtenaw Community College in Ann Arbor, Michigan. This phantom, which consisted of a human skeleton encased in tissue-equivalent plastic, is shown in Figure 3-2. This phantom also had to be augmented with a thickness of 1 1/2 in. of water to be representative of a human adult.

3.2 RADIOGRAPHY BELOW 300 kVp

All of the initial tests below 300 kVp were conducted with the radiological phantoms and the water containers. The tests attempted to establish the limits of:

1. Weapon detectability as a function of body width, position, and gun size

2. X-ray filter requirements

3. Collimation requirements.

With regard to item 1, other things being equal, the ability to detect a concealed weapon on a target is most strongly dependent on where the weapon is located on the target. The experiments with the radiological phantoms and weapon location showed that weapons could be detected with < 1 mR dose around arms, behind arms, under arms, or around the chest area; however, the pelvic region required > 1 mR dose to detect weapons.

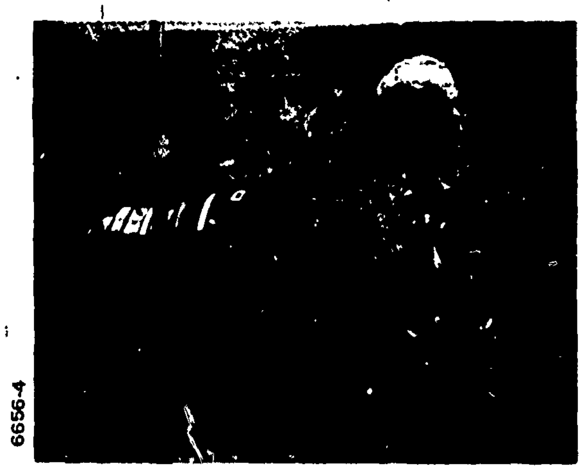


Figure 3-1 Radiological Phantom Used for Early Tests

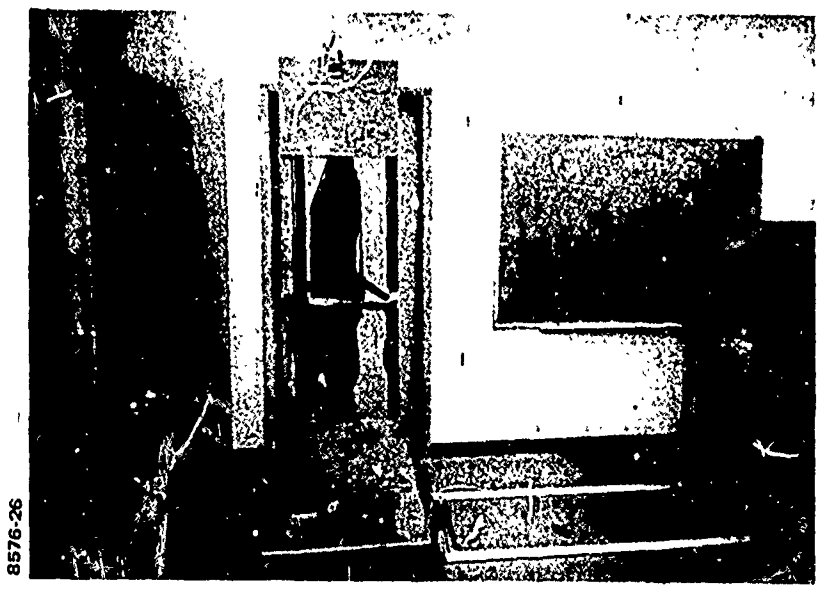


Figure 3-2 Radiological Phantom Used in System Evaluation

The ability of a given energy X-ray beam to penetrate these targets was found to depend on their thickness. For example, no serious degradation of the imagery was apparent up to about 7 in. of thickness with 160 kVp X-rays. Based on these findings, the optimum inspection geometry had the target directly facing the X-ray source (or directly away). This result was determined to be valid within a small angle. If the target faced 90° to the beam, in addition to presenting a thick (≈ 18 in.) target along the beam, a very narrow portion of the fluorescent screen was in shadow, which greatly increased the dynamic range problem in the video section of the detector.

Figure 3-3 shows the typical effect of water thickness on X-ray penetration, scattering, and the ability to discern the outline of a weapon. These data are typical of the results obtained with the filled plastic watercontainers for a single pulse of 150-kVp, 4-mA X-rays (≈ 1mR); Figure 3-3 (a) is representative of a 7-in. thickness of water, which would correspond to a very thin human adult. Figure 3-3 (b) corresponds to the water thickness in the abdominal region of a 200-lb adult; the experimental water thickness was 14-in. The greater water path length caused a substantial amount of incoherent X-ray scatter, thus diminishing the information content of the image. It should be noted that these data were obtained at the output of the image intensifier tube and not through the video display.

A gun is discernible in the abdominal region of the radiological phantom shown in Figure 3-4. In this case, no additional water thickness was used. The lighter areas in the thoracic region of the phantom indicate less X-ray absorption, so that if the gun were located in that region, it would stand out even more clearly. The clavicle region, or shoulder area, is seen in Figure 3-4 to be very dark, which is indicative of apparent high X-ray absorption; however, a geometrical property of the X-ray beam contributes in large part to the observed darkening as follows. The X-ray beam emanating from the source located about 10 ft away from the screen may be regarded as a right circular cone with a 40° vertex. The vertex of the cone is located at the X-ray source. The longitudinal axis of the cone is directed at the pelvic region of the phantom. The intensity of the X-ray beam is greatest along the longitudinal axis; the intensity gradually diminishes toward the edges of the cone by a factor of two, finally, at the edges. Thus, a small weapon placed in the shoulder region, away from the relatively transparent lung cavities, could present a detection problem. Experimental cases were set up according to these considerations and culminated in the results just described.

Work, concerning X-ray filter requirements, was done with various metals and variations in their thickness. The effects of X-ray filtration are described as follows: if a thin sheet of metal is placed in the beam of X-rays, the intensity of the beam is reduced and the spectral character of the beam is altered; such

(a) 7 in. of H_2O

9521-1

(b) 14 in. of H_2O

Figure 3-3 Effect of Water Thickness on X-Ray Penetration

9521-2

Figure 3-4 Radiograph of Phantom
(Gun in Pelvic Region)

sheets used intentionally to modify the spectrum and intensity are called filters. The amount of radiation absorbed in the filter depends upon the thickness and atomic number of the material and the wavelength of the radiation. The absorption is greater in thicker filters and materials of higher atomic number; it is also greater for radiation of longer wavelengths or lower energy.

When a beam of heterogeneous radiation is filtered, all the wavelengths are reduced to some extent, but the less penetrating radiation experiences the greatest absorption. Thus, the spectrum is modified. The effect of filtration is seen in Figure 3-5. The filter reduces the total intensity of the beam, but the reduction is greatest at the long wavelength, or low energy end of the spectrum.

The result is that after filtration, the less intense beam has a greater proportion of the shorter wavelengths and the predominant wavelength is of shorter wavelength. Hence, the beam of reduced intensity is relatively more penetrating.

Aluminum is the metal most commonly used in radiography. Metals of higher atomic number than aluminum are required for beams above 120 kVp. Copper is used up to 200 kVp, tin for beams at 200 to 400 kVp, and lead from 800 kVp up to about 2 MeV. These metals are not sufficient alone, however. The high-energy photons in the X-ray beams are able to ionize the inner electron shells of the atoms in the filter material, and the filter omits characteristic X-rays. This characteristic radiation could easily be absorbed in a subject's tissue, and may be intense. To absorb this characteristic radiation from the primary filter, a secondary filter needs to be added. Such filters made of two or more metals are composite filters. Copper filters usually have a secondary filter of aluminum. This requires the addition of copper and aluminum. Lead filters used above 800 kVp have secondary filters of tin, copper, and aluminum.

Most of the experimental work was performed with aluminum and iron filters. Figures 3-6 and 3-7 show a comparison between the use of a 0.182-in.-thick aluminum filter and a 0.040-in.-thick iron filter. The weapon was placed behind 9 in. of water in plastic containers. The X-ray dose in a single pulse was approximately 1 mR at 150 kVp, 4 mA, for each case. The attempt to increase the penetrability of the X-rays by going from aluminum, as shown in Figure 3-6, to iron, as shown in Figure 3-7, did not produce a significant difference; moreover, the reduction of X-ray intensity in each case caused considerable loss of contrast in the resulting images. The ratio of X-ray transmission to X-ray scattering in Water at the X-ray energies used also contributed to the information loss in the images. The primary useful net effect in the use of filters was dose reduction; increase of penetrability in the water was at best a secondary effect.

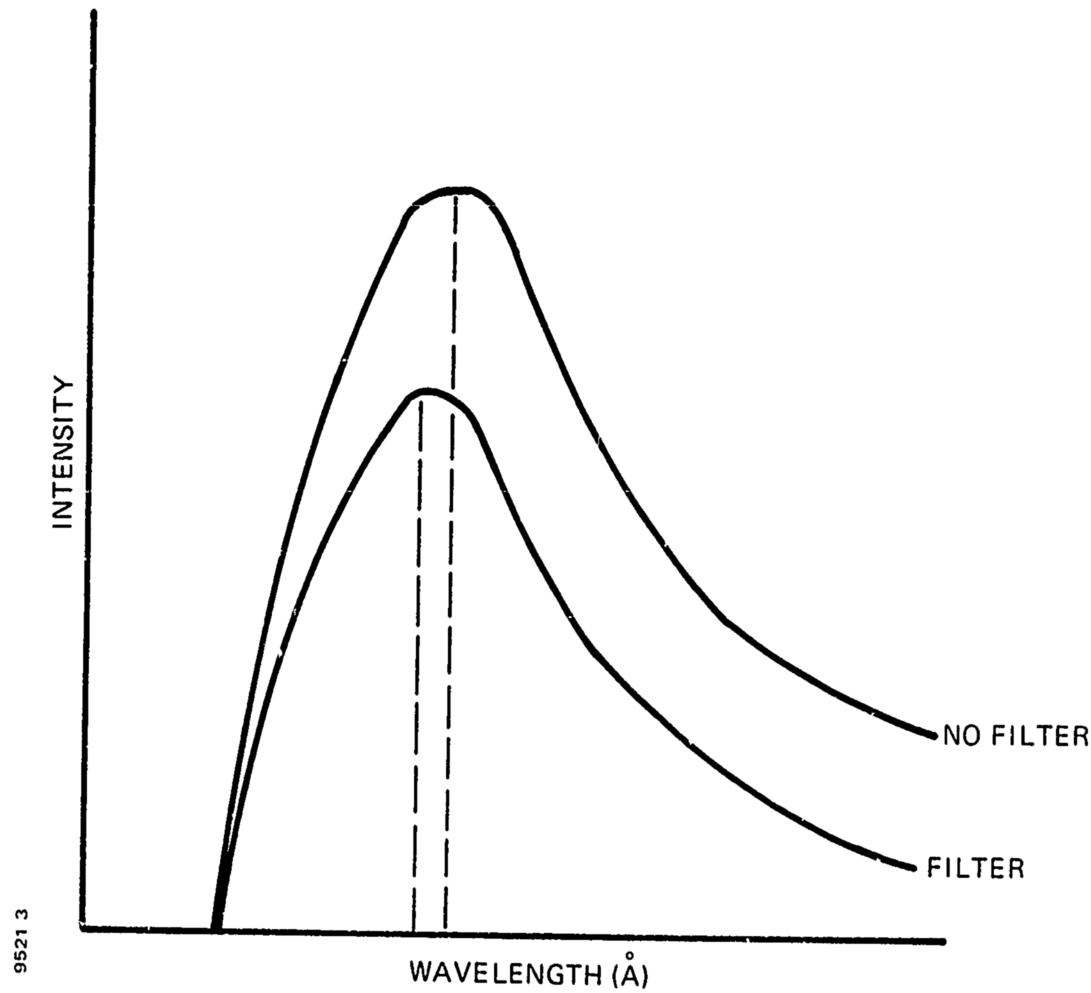


Figure 3-5 Effect of Filtration on Intensity and Spectrum

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Figure 3-6 0.182-in. Aluminum Filtration (9 in. of H_2O, 1 Pulse at 150 kVp, 4 mA)

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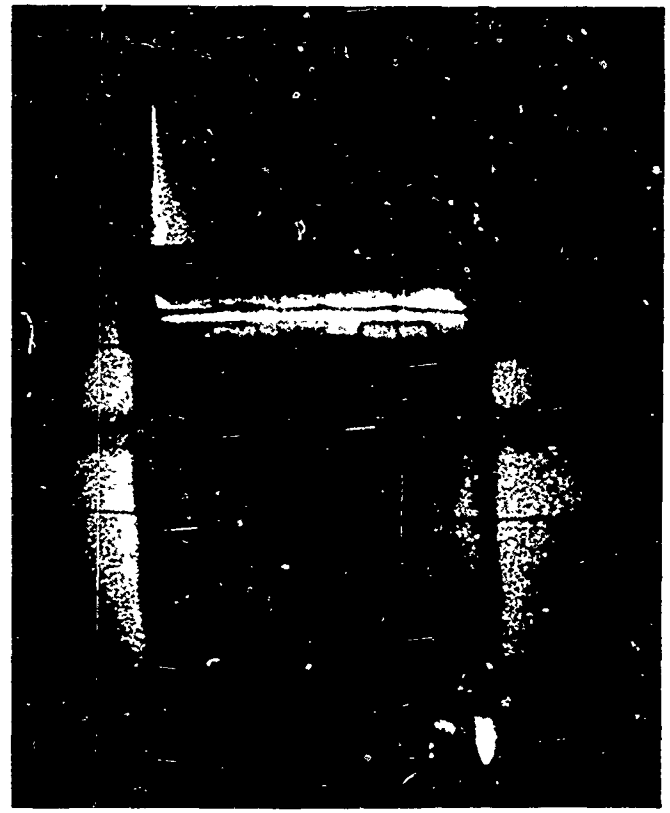

Figure 3-7 0.040-in. Iron Filtration (9 in. of H_2O, 2 Pulses at 150 kVp, 4 mA)

As to collimator requirements, it was found that X-rays which struck the PFG screen without passing through the target gave rise to very intense highlights in the imagery, which also caused a severe loss in contrast and the ability to discern details in images. An example of this effect is shown in Figure 3-8, in which the phantom is shown. Highlight areas are seen around the shoulders, head, and neck, between the arms and the body, and the legs. If the dose was reduced to attenuate highlights, it became insufficient to detect weapons. If the dose was raised to detect weapons, the highlights caused difficulty in image contrast. A partial solution was found in providing a collimator at the source. This consisted of lead plates to limit the width of the X-ray beam at the target. Figure 3-8 shows how the highlight is reduced at the arms of the phantom to the edges of the screen. Had this collimation not been present, the highlight would have been such that even recognition of the phantom would have been difficult.

3.3 MINIMUM WHOLE BODY DOSE

The dose required to distinguish clearly a concealed gun on a radiological phantom target was determined to be strongly dependent on three conditions at the same time: (1) the position of the weapon on the target, (2) the thickness of the target, and (3) the type of gun. The dependence of the radiation dose on the X-ray spectrum and X-ray peak voltage (and thus X-ray machine) was observed to have secondary, yet related, effects.

The most critical of the three factors was by far the first. It became quite apparent after the first series of dose measurements that, while guns could be detected under the armpits, behind the arms, or around the chest area of a given individual or phantom with doses well under 0.1 mR, the pelvic region required doses of 1 mR or higher. The water-equivalent thickness in the abdomen was determined to be the most critical parameter in determining the minimum dose required for acceptable contrast.

Almost a one-to-one equivalence of this region to water was determined using specifically prepared plastic water containers of graduated thicknesses. The dose required to penetrate thus became easily definable by standard curves of half-value layer (HVL) for water (the thickness of a specified material which, when introduced into the path of a given beam of radiation, reduces the radiation transmission in half).

For example, for 100-keV photons, the HVL is about 3 cm. Thus, for every additional 3 cm of abdomen thickness the doses would increase by a factor of two. The important point to note is that as the energy goes up the HVL increases. Thus, at 500 keV, the HVL is 7 cm, greatly decreasing the necessity for dose variation as the width of the individual changes. The dependence of HVL on photon energy is illustrated in Figure 3-9.

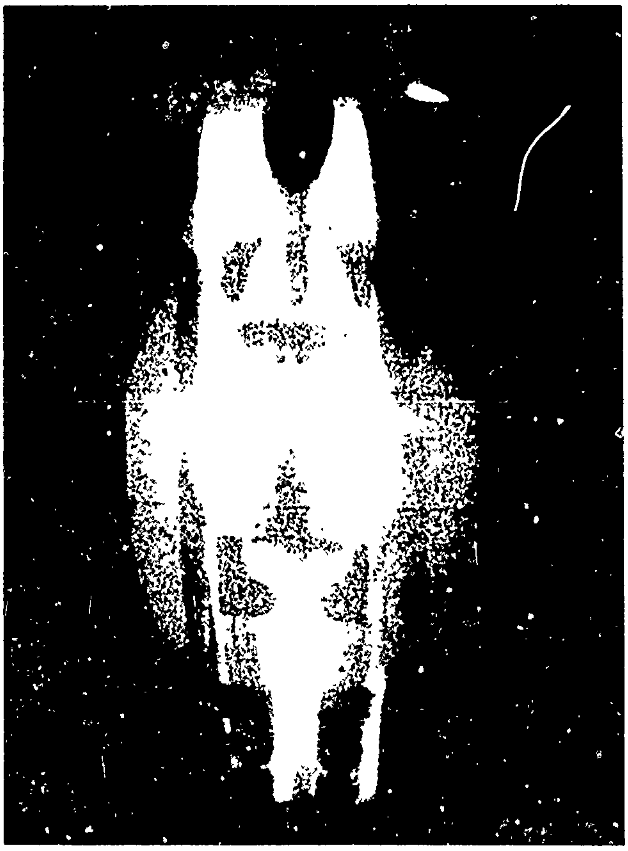

Figure 3-8 Example of Highlight Effect on Image Contrast

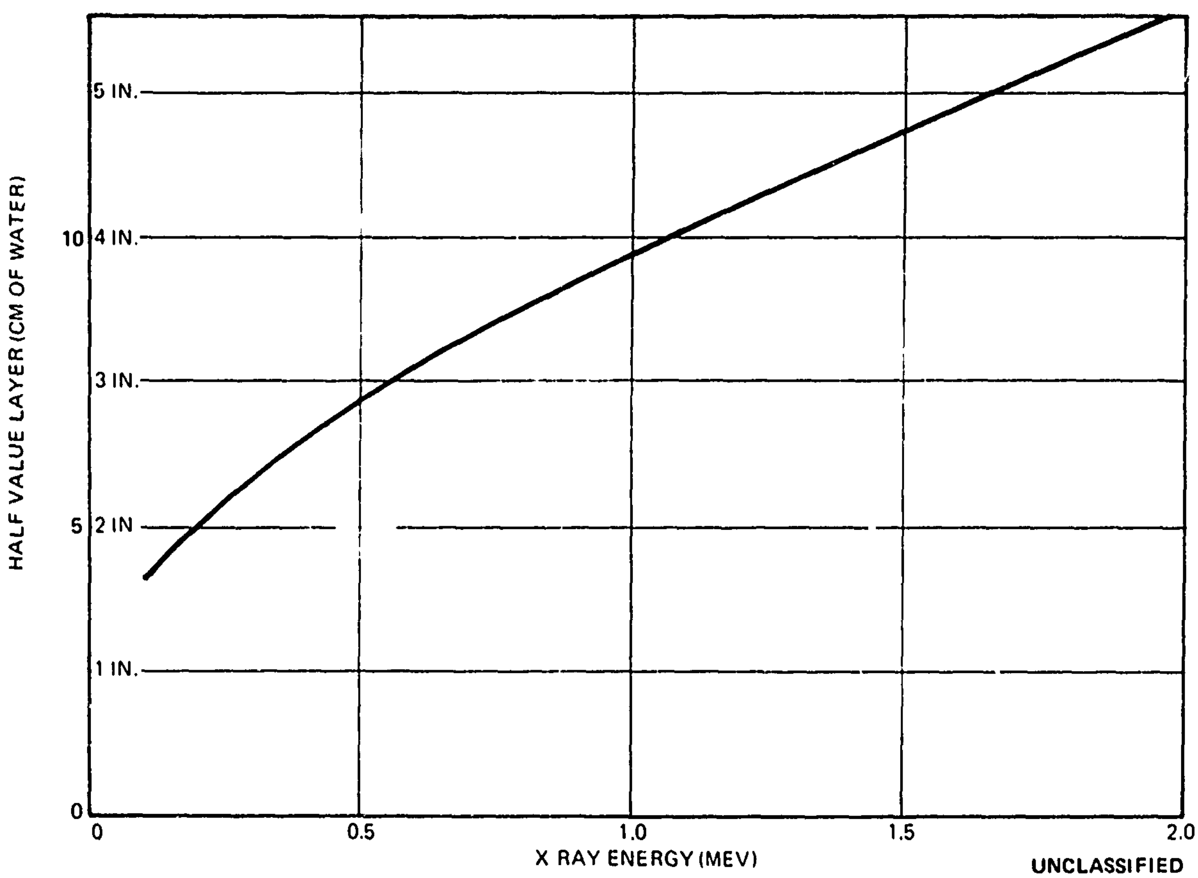

Figure 3-9 Half-Value Layer for Water

As the X-ray voltage goes up, it should be possible to observe less need to vary the dose from individual to individual and the maximum width of a person capable of being inspected should increase with X-ray energy. Thus, 2 mR of 300-kVp X-rays would be necessary to see a gun on the abdomen of a 190-lb real person. Yet the same 2 mR of 300-kVp X-rays would yield a good pulsed image of a gun on an individual who weighs of 120 lb. The 1-MVp tests in the Army experiments, with the plastic-equivalent phantom augmented with up to 7 in. of water, showed that much wider individuals could be inspected with smaller dose variations and higher X-ray energies.

The minimum dose dependence on the suspect is a function of the weapon one is seeking to detect. Here the dose dependence could be reduced to an equivalent lowest common denominator, a .22 caliber revolver. Most of the weapons used, at least in the barrel, were as dense to X-rays as this small revolver. All the automatics used had a much higher cross-section for all the X-ray voltages examined and thus gave higher contrast images.

The minimum single pulse dose expected on a suspect, therefore, has to be set and defined by the worst suspect conditions, viz., a small revolver carried on the abdomen of the fattest person that would have to be inspected. If this restriction is not made, it becomes very easy to quote extremely low dose figures (like 0.03 mR per pulse, which is quite valid for the acquisition of a high-contrast image of a 38-mm automatic on the chest of a bone and water phantom and yet is totally inadequate for more challenging conditions). Secondly, the voltage must be high enough to permit penetration with a given minimum dose to the subject.

The minimum dose for any given subject thus depends on:

1. Sensitivity of the detector
2. Minimum X-ray pulsewidth capable of producing a single field of information
3. X-ray voltage
4. Capability to see a .22 caliber weapon in front of at least 9 in. of water, and preferably 12 to 14 in. to ensure visibility of persons above 250 lb or thinner persons with their arms across their bodies.

Since a definable minimum safe dose does not exist, the minimum doses used in this program are compared to radiation levels to which man is exposed for medical, industrial, and environmental reasons. These data are compared in Table 3-1. 3-1.

TABLE 3-1

RADIATION EXPOSURE DATA

1.	Expected SST Exposure	
	Attitude (ft)	Dose per Hour
	30000	0.29 mR
	50000	0.84 mR
	70000	1.80 mR
2.	Medical Examples	
	Chest X-ray	504 mR
	Barium Enema	629 mR
	Upper GI Series	519 mR
3.	USAEC Limit on General Population	500 mR/year
4.	Normal Sea Level Background	
	Ocean	50 mR/year
	Land	150 mR/year

3.4 X-RAY SCATTERING

Scattered X-radiation results in the obscuration of the radiographic record, producing significantly degraded contrast. In the case of all the X-ray energies evaluated in this program, Compton scattering is the dominant factor in scattered radiation. Because all the radiation is produced as spectra with varying amounts of low-energy components, scattered X-rays from the suspect, and to a secondary degree, from the walls, floors, and ceiling of the inspection area, will be encountered.

Scattering occurs both as large angle scattering, in which there is a considerable difference in direction between the impinging and scattered X-ray, and small angle scattering. Tests were performed throughout the program to assess the relative extent of the scatter produced by the environment and by the subject itself.

3.4.1 Room Scattering

Tests performed with nearly all of the X-ray sources evaluated in the program indicated that there was small, albeit measurable, scatter from the environment. This was detected as a pulse of light produced in the detector with the screen taken out of the direct radiation and pointed to one of the walls, or the ceiling, etc. The effect, in all cases, was shown to be not due to the activation of the image intensifier or the TV camera. This was done by the simple process of capping the objective lens during the test. The light produced was thus deemed to be due to a scatter background produced on the screen. The amoung of light produced was barely discernible at the usual TV tube beam level settings for pulsed image reception. The effect could be greatly enhanced by changing camera settings; however, such settings would result in seriously degrading the dynamic range of the vidicon and are not applicable.

Some tests were performed with the 150-kVp machine with lead walls, tubes, and curtains to attempt to isolate and shield from environmental scattered radiation. No discernible reduction of light was noted although a series of complex shields was tried. It would appear, therefore, that although some environmental scatter effect exists, the effect is not serious and is very difficult to eliminate by using shields.

3.4.2 Subject Scattering

The scatter of X-rays in the subject itself was found to be the single largest cause of loss of radiographic contrast in the whole subsystem.

Attempts were made to absorb this scattered radiation (which is generally of very low energy) by using thin layers of high atomic weight material, such as lead, in front of the detector screen. A variation of these filters, known as Lysholm grids, which are composed of strips of lead interspersed with plastic, was also attempted. The lead strips act as absorbers of large angle scatter which has to travel through greater lengths of lead.

At X-ray voltages below 300 kVp, both of these techniques were found to have no value. Contrast did not increase appreciably. Beneficial effects from the use of thin layers of lead first became evident at X-ray voltages above 600 kVp.

At 1 MVp in the Army experiment, it was experimentally shown that a layer of lead foil 8 to p5 mils thick reduced the scattered radiation from the phantom and increased the contrast between a gun and the target.

The major technique for reducing the scattered radiation from a target at any of the inspection voltages used, was found to lie in the elimination of large angle scatter. This was affected by locating the suspect a good distance away from the detector screen. It was found that contrast improved appreciably at source-to-target distances above 2 ft. Distances much larger than 3 ft did not improve contrast further and started to result in magnification problems.

Small angle scattering is, of course, encountered within the object being radiographed and is quite difficult to minimize. However, as the Compton absorption contribution diminishes with increasing X-ray energy, so does the Compton scattering effect. The ratio of scattered to direct radiation per unit length of any given material is a decreasing function up to X-ray voltages of around 2 MeV. Thus, from the viewpoint of loss of contrast due to small angle scatter it is also important to inspect with relatively high X-ray energies.

SECTION 4

CONCLUSIONS AND RECOMMENDATIONS

4.1 CONCLUSIONS

4.1.1 General Conclusions

The feasibility of the concept was investigated using a variety of handguns and two types of full body phantoms. When the phantom faced the X-ray beam, the radiographic subsystem gave real-time, single-pulse TV images in which the weapons had high enough contrast to be discernible over the densest part of the phantoms, the pelvic region.

Dose measurements taken during the radiological phantom test showed that the breadboard radiographic systems used resulted in X-ray dose exposures to the subjects of between 1 and 4 mR under the various test conditions for good contrast image.

4.1.2 Radiographic Subsystem

The matrix of radiographic subsystem components shown in Table 4-1 was evaluated to determine the optimum radiographic subsystem for weapon discrimination that could be assembled at this time. The optimization of the radiographic subsystem was obtained experimentally. The first item on the table was used as the fiducial system. This is a continuous X-ray source recording on 525-line video tape producing a TV image of a phantom carrying guns. Subsequent single-pulse images were compared to a single frame of the continuous data.

Three elements of the radiographic detector subsystem are common to all configurations discussed below. These are the fluorescent screen, the objective lens, and the image intensifier. The empirical evaluation of these three elements preceded the test series discussed below and resulted in the establishment of the baseline system.

4.1.2.1 Screen Material

ZnCdS was chosen for the fluorescent screen material, based on maximum light output for a given X-ray dose at the energies of interest and the inherent ruggedness of this type of screen.

TABLE 4-1

MATRIX OF RADIOGRAPHIC SUBSYSTEM COMPONENTS

System No.	Camera (TV lines)	Recorder[1]	Display	Synchronizer[2]	Source	Remarks
1	525	CWVTR	525	None	CW	Standard for Comparison
2	525	Lithocon	525	None	CW	Show Lithocon Capability
3	525	SPVTR	525	Old	Mechanical Shutter	Baseline System
4	525	Lithocon	525	Old	Mechanical Shutter	Show Lithocon Capability
5	525	SPVTR	525	New	Electronic Pulse	Test Short Pulse-Integrate
6	525	Lithocon	525	New	Electronic Pulse	Show Lithocon Capability
7	525	Lithocon	525	New	Mechanical Shutter	Check New Synchronizer
8	525	SPVTR	525	New	Mechanical Shutter	Check New Synchronizer
9	1029	Lithocon	1029	New	Mechanical Shutter	Check 1029-Line TV
10	525	SPVTR	525	New	Electronic Pulse	FAA System Check
11	1029	Lithocon	1029	None	CW	Check 1029-Line TV
12	1029	Lithocon	1029	New	Electronic Pulse	Improved System Check
13	525	None	525	None	Visual Light	TV Camera Checkout
14	1029	None	1029	None	Visual Light	TV Camera Checkout

NOTES: (1) SPVTR: Single Pulse Video Tape Recorder, CWVTR: Continuous Video Tape Recorder.

(2) Old: No TV field integration capability, only time delay; New: Time delay plus up to five fields of video.

4.1.2.2 Objective Lens

The two objective lenses tested were an f/0.95 Canon and an 18-mm custom-built f/1.5 Angenieux. A lens similar to the latter but with an aperture of f/1.0 is possible. The short focal length coupled with the unusual 38-mm format diameter, results in a 93° field of view. This is required to view the large (8-ft) screen formats with a reasonable over-all detector length.

4.1.2.3 Image Intensifier

The image intensifier selected was a three-stage, magnetically focused device. This tube was chosen for its high gain and minimum distortion, compared to electrostatically focused devices. Future improvements in the magnetic tubes in the areas of gain, resolution, and input-output interface are feasible.

4.1.2.4 X-Ray Source

Using a system based on the above three elements, many experiments were performed to determine the optimum X-ray source characteristics. Both thermionic emission and field emission X-ray sources were studied. Tests were performed with variable voltage machines with voltages going up to 300 kVp. The conclusion reached was that X-ray voltages between 700 kVp and 1 MVp are necessary for the system to have universal usage, a conclusion based on work performed for the US Army on the IACS Program.

4.1.2.5 X-Ray Pulse Production

Two techniques of pulsing thermionic emission X-ray sources were investigated. The first involved a solenoid-driven lead shutter with a nominal open time of 0.1 sec. This simple technique gave reliable and repeatable shutter opening with no radiation being emitted from the source in the closed position. The second technique involved the electronic pulsing of a thermionic emission 150-kVp X-ray source. X-ray pulses up to 15 msec in length were obtained by pulsing the tube plate voltage. This was done by having the filament voltage on continuously as well as keeping a small supply voltage on the plate prior to pulsing. It was also noted that the output spectrum appeared to be softened by the technique employed.

The electronic pulsing technique severely limited the range of time adjustment because of the impulsive electrical loads imposed and, thus, pulses larger than 15 msec were not available. Although the radiation has a harder spectrum than the field emission type device, the dose per pulse (0.1 mR at 7 ft

vs. up to 5 mR) was significantly lower than that from the mechanically pulsed machine.

The conclusion reached, therefore, is that electronic pulsing is feasible at 150 kVp and that further work in the area of increasing dose per electronic pulse could be fruitful. However, it is not known at this point whether 300-kVp or higher hot cathode machines can be pulsed electronically. Also, unless the inspection geometry requires extremely short pulses (which they do not at this point), it is far more efficient to use mechanical shutters which are cheap, reliable and more flexibile in adjusting pulsewidth. It is also quite clear that the mechanical shutter must be improved to give shorter and spatially more uniform pulses.

4.1.2.6 Television Camera

The other variables in the matrix involved the TV camera resolution, the recording device resolution and performance, and the electronic control and synchronization. The 525-line TV camera performance was contrasted against the performance of a 1029-line video system. The 1029-line camera was determined to be unacceptable as a component of the detector because of its extremely poor sensitivity. There are three possible explanations for the poor performance of the camera:

1. Inherent poor performance in the low-light conditions present in the intensifier output

2. Increased S/N ratio due to the larger signal bandwidth

3. Possible mismatch between the response of the vidicon of this camera and the output phosphor of the image intensifier.

In an attempt to compensate for this apparent lack of sensitivity, a single-stage Bendix diode intensifier was adapted to the 1029-line camera input. No significant improvement was noted in the performance of the system. The investigation in this area was halted pending the evaluation of a 1029-line display system, the lithocon.

4.1.2.7 Storage Device

The performance of the lithocon (which is a solid-state recording device that records images on a silicon matrix) was evaluated against that of the video tape recorder. The lithocon is capable of operating at both 525 lines and also at 1029-lines. At 525 lines, the performance of the lithocon was determined to be

equivalent to the performance of the tape recorder, except in one vital respect: the dynamic range of the lithocon is considerably narrower than that of the video recorder. This resulted in a serious degradation of over-all contrast when viewing targets with bright surroundings. Bright surroundings were an inherent problem in many of the target configurations, since any given suspect has a different outline and could have a comparatively different position with respect to the detector screen.

It was thus concluded that, although the lithocon offers a higher resolution capability, unless the dynamic range problem can be solved or alleviated it would not offer an improvement to the radiographic subsystem. Since the lithocon is the only display and/or recording component available on the market today capable of higher than 525-line resolution, the attempt to improve the 1029-line TV system performance was not pursued further. The present conclusion is that, unless the performance of the lithocon can be changed, there is no point in increasing the TV pickup resolution beyond the nominal 525 lines. Finally, from an experimental viewpoint there does not appear to be any indication that the problem of concealed weapon detection is one of resolution. The areas requiring further improvement fall in the categories of contrast and/or gain and, of course, dynamic range or elimination of the effects of bright surroundings.

4.1.2.8 Synchronization Electronics

The last part of the electronic components examined in the matrix of Table 4-1 involved the synchronization of the pulse signal from the X-ray source with the correct frame on the TV recorder and the collection of all of the TV frame information onto the recording medium. Since the vidicon photosensitive surface has a long decay time (which varies with the intensity of light hitting it), there is more than one field of information available to the recording medium.

Experiments indicated that the brightest field is the fourth or fifth one from the beginning. The conclusion reached was that the lag in the vidicon pickup resulted in less than a maximum signal being developed on the video output during the duration of a very short or very weak pulse of light. This conclusion is further borne out by video signal measurements which show that the video level in a given number of frames during a pulse is less than the video level contained in the same number of frames pulled out of a continuous sequence. The time delay circuits must thus be carefully set to give the optimum field for a recording.

The last area to be explored during this experimental parametric analysis was to collect all the information produced by the X-ray pulse, either on the photosensitive surface of the vidicon or on the surface of the lithocon. Electronic circuitry was devised which would allow TV fields to be stored on the

photosensitive surface of the vidicon and read out after the end of the pulse information on the output of the intensifier. The synchronizer stored up to five fields. Concurrently, time delay and amplification circuits were designed and assembled to permit storage directly onto the lithocon for the complete duration of the pulse.

The conclusions reached on evaluating the effects of integration were that: (1) in the case of video tape recorder storage, the technique was quite effective for very low light signals at the output of the intensifier; and (2) the dynamic range of the lithocon resulted in more pronounced degradation of over-all contrast when integration of more than one field of video signals was attempted. The whites become more pronounced and wipe out any contrast left in the darker regions of the image.

The over-all conclusion reached, based in part on the data from the concurrent Army Effort, in the case of the radiographic subsystem is that a pulsed source of 700 kVp to 1 MVp, ZnCdS screen, an objective lens allowing the maximum aperture with as low a focal length as is possible (to allow a short front end), a magnetically focused intensifier to provide low distortion and high gain, an efficient 525-line TV system using either fiber optics or a low-light-level TV camera (and the electronics described in the above section) coupled to a 525-line TV monitor and single pulse video tape recorder would provide the optimum image for radiography. Specifications are presented in Section 4.2.

4.1.3 Inspection Geometry

4.1.3.1 Angular Geometry Constraints

The radiographic subsystem performance evaluation tests were conducted with the phantom placed at various angles with respect to the screen and also by placing the phantom at various angles with respect to the X-ray beam. The former did not pose much of a problem; however, in the latter case, imagery degraded rapidly as the phantom was rotated to angles out of the perpendicular to the X-ray beam.

As the body assumes these off-angles, the X-ray beam has to traverse a much larger portion of tissue and, thus, penetration becomes increasingly difficult. Unless the gun is at a propitious place on the body, making it stand out against an air background, contrast is too low for weapon discrimination. The experiments showed that X-ray beam angles with respect to the body of up to about 20° from the normal are the most that can be tolerated.

The experiments involving the relative position of the X-ray detector screen with respect to the body (with the X-ray hitting the body head-on) showed

that these geometries simply resulted in a horizontal expansion, i.e., differential magnification, of the body. There was no discernible attenuation change across the surface of the body. It is thus concluded that off-angle positions of the screen would simply mean that larger screen widths would be required to cover the full girth of the suspects.

4.2 RECOMMENDATIONS

4.2.1 Radiographic Subsystem

The radiographic subsystem recommended consists of a pulsed X-ray source; a fluorescent screen, which converts the X-rays to light; an objective lens which images light from the fluorescent screen onto the photocathode of an image intensifier tube; a transfer lens or fiber optics which images light from the output phosphor of the image intensifier tube onto a TV camera; a TV camera which provides electrical output signal to the recording or storage medium; single-pulse tape recorder storage; and a monitor to display the stationary image.

4.2.1.1 Screen Selection

The criteria employed in the selection of a screen material were: (1) an effective light yield per incident X-ray and (2) the adaptability of the screen to the operational requirements. Another consideration in the selection of a radiographic screen was also its inherent resolution. However, screen resolution can be shown to be not significant in the problem of inspection for concealed weapons because: (1) the resolution is limited by other system components because of the large screen-to-photocathode minification employed to the system; and (2) an equivalent screen resolution of the order of 3 ℓ p/mm is sufficient to satisfy the objective. On the other hand, the ruggedness of the screen is an important consideration as the system has to be transported easily and set up in various locations.

Experimental evaluation of the effective light yield from the varieties of screens that were available (including the alkali halides, sodium iodide, cesium iodide, and powders of fluorescent materials, such as zinc sulfide, zinc cadmium sulfide, and calcium tungstate) showed conclusively that the most effective fluorescent material was ZnCdS. This, coupled to the other considerations such as resolution and ruggedness, make ZnCdS the recommended screen for this application.

4.2.1.2 Objective Lens

The best means of improving system performance (and thus reducing

dose requirements) is to select as low an aperture objective lens as is practicable. The second requirement on the objective lens is that it have a low focal length to permit the distance between flourescent screen and objective lens to be kept short. The feasibility of manufacturing such a lens has been shown. The f/1.5 lens (which was specially designed for the FAA system) has an 18-mm focal length and images a full 8 ft at a distance of 4 ft from the screen and gives a very flat field image on the surface of the photocathode of the image intensifier. This lens, which was specially made by Angenieux in France, is the best lens available as far as the uniformity of image and distortion are concerned. As a result of various analyses performed by the lens manufacturer and experimental data obtained during this program, it is concluded that the lens aperture could be increased to f/1.0. This change will give an improvement factor of at least 2.25 in light collection efficiency, and based upon the experimental results, probably over a factor of 3 reduction in dose.

4.2.1.3 Image Intensifier

The experiments performed during the present study effort indicated that the three-stage, magnetically focused image intensifier, because of its much higher gain and much lower distortion, is far superior to a three-stage electrostatically focused tube for this application. The selection of ZnCdS as the screen material makes the selection of photocathode response most suitable for a transfer of this spectrum of light to be the S-20 response. The output phosphor most suitable to coupling to a TV camera under this condition is a P-20 aluminized phosphor.

The limiting resolution of the image intensifier has also been determined as a result of the various tests. Minimum resolutions of 25 ℓp/mm at the center and 18 ℓ p/mm at the edge are recommended.

The luminous gain of the intensifier is used to convert the screen output to the radiant energy necessary for exposure of the TV camera. Present laboratory experiments with the radiographic subsystem breadboard were conducted with intensifier tubes having gains of up to 500,000. The characteristics of these image intensifiers are those of the RCA C70021 ZP1. The image intensifier recommended for the IACS is therefore an RCA C33085 AP2 three-stage, magnetically focused tube having a gain of 600,000 and limiting resolution of 40 ℓ p/mm. A parallel recommendation is to have the output phosphor of the image intensifier be on a fiber-optic faceplate, allowing fiber-optic coupling to the TV pickup of the radiographic subsystem. This latter capability could, however, result in a factor of 2 loss in image intensifier gain. A tradeoff must therefore be made between lens and fiber optics prior to final intensifier gain selection.

4.2.1.4 Transfer Optics

The function of the transfer optics is to transfer the image on the output phosphor of the image intensifier to the photosensitive surface of the TV tube. The present breadboard uses an f/0.95 lens for this purpose, since the magnetic tube output phosphor is on a flat glass plate, and not a fiber-optic surface. A theoretical minimum loss for such a system is a factor of 4. As was discussed above, fiber optics could be used in place of the lens. If selected, the recommended transfer optics would have to be a bundle with a 35-mm-diameter face on one end and a 16-mm-diameter face on the other. A bundle length of 3 in. is considered minimal due to the high voltages present at the output of the intensifier. The resolution of the tube corresponds to fiber size of about 12 mm or less. The provision of more light to the TV camera should result in improvements in the performance of the tube by the fact that the signal to the vidicon is increased and one is operating outside of the noise region.

4.2.1.5 Television Camera

The TV camera which has been found to be the most versatile is the basic vidicon. The vidicon is a much simpler camera to use and is more amenable to automatic corrections and to acceptance of synchronizing signals than is the orthicon class of tubes. The tube recommended for this application is an 8507 type tube. It is a separate mesh vidicon which yields a fairly uniform image (after suitable adjustments in beam alignment) in the presence of the magnetic field of the image intensifier.

An alternate means of increasing the sensitivity of the back end of the radiographic detector is a low-light-level TV camera. Tests conducted with low-light cameras including the Isocon (a derivative of the orthicon) and the intensified vidicon indicate that low-light-level cameras could be used to reduce the dose required for a given contrast level, or to allow higher light levels to reach the vidicon, and improve its modulation transfer characteristics. The most simple tube of this type is an intensified vidicon (or a vidicon with additional stages of intensification ahead of it).

4.2.1.6 Storage Medium

A Sony 310 video tape recorder is recommended with the modifications described in Section 2.7.1.

4.2.1.7 X-Ray Source

None of the sources studied are recommended. Although the Balteau-graph 300-5, No. E-334D, thermionic X-ray unit could be used with a mechanical shutter, it would be of limited value for people weighing more than 200 lb. It is recommended that a compact pulsed X-ray source be developed to produce 700-kVp to 1-MVp X-rays capable of delivering a dose of between 4 and 8 mR at 1 m. It is recommended that field emission type device be used, thus eliminating the mechanical shutter requirement.

4.2.2 Architectural Requirements

In the case of the radiographic subsystem, it is recommended that the source and the detector be placed behind not more than 1/4 in. of plywood to ensure minimum absorption of X-rays through the wall material. Other materials, such as wallboard or sheet aluminum, which have been used during the experiments, affect both the transmission and scattering properties of the X-rays and are thus not recommended.

4.2.3 System Specification

The component specifications of the radiographic subsystem as determined above are given in Table 4-2.

4.2.4 Final Recommendations

It is recommended that detector system prototypes be developed having the specifications presented. It is also recommended that additional storage be provided to permit the capability of recording a new frame while the early image is on display, allowing adequate observation time in cases of more than one person moving rapidly through the inspection area.

It is recommended that the following developments also be carried out concurrently so as to lead to an optimum radiographic detector system:

1. Development of a high-voltage pulsed X-ray source to produce X-rays with energies between 700 kVp and 1 MVp with a dose of 4 to 8 mR at 1 meter

2. Evaluation of fast response vidicons (Tivicon, silicon matrix vidicon) to eliminate lag time in short-pulse exposures

3. Evaluation of dynamic range and bright surround improvement

by video signal processing, specifically grey level expansion and clipping techniques

4. Selection of low-light-level TV cameras or fiber optics

5. Operational system evaluations including full-scale inspection mockups, to include an appropriate early warning magnetic detector.

TABLE 4-2

COMPONENT SPECIFICATIONS

Component	Manufacturer	Model	Remarks
X-ray source			To be developed
Fluorescent Screen	US Radium Co.	PFG	ZnCdS, 3 by 8 ft
Objective Lens	Angenieux		18-mm, f/1.0, 38-mm image
Intensifier	RCA	33085	600 K gain, 40 ℓ p/mm
	or		
	RCA	33074	2000 K gain, 25 ℓ p/mm
Transfer Optics	Canon or		50 mm, f/0.95
	Optics Technology		35- to 16-mm fiber-optic reducer
Vidicon	GE	8507A	Separate Mesh
TV Camera	Sylvania	800	Modified per Section 2.6.1
Recorder	Sony	EV310	Modified per Section 2.7.1
Display	Conrac	CKD14	Modified to Accept Single Field Inputs

(Continue)

TABLE 4-2 (CONT.)

COMPONENT SPECIFICATIONS

Component	Manufacturer	Model	Remarks
Synchronizer			Per Section 2.1.8
Integrator			Per Section 2.1.8
Shutter			Per Section 2.1.2

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